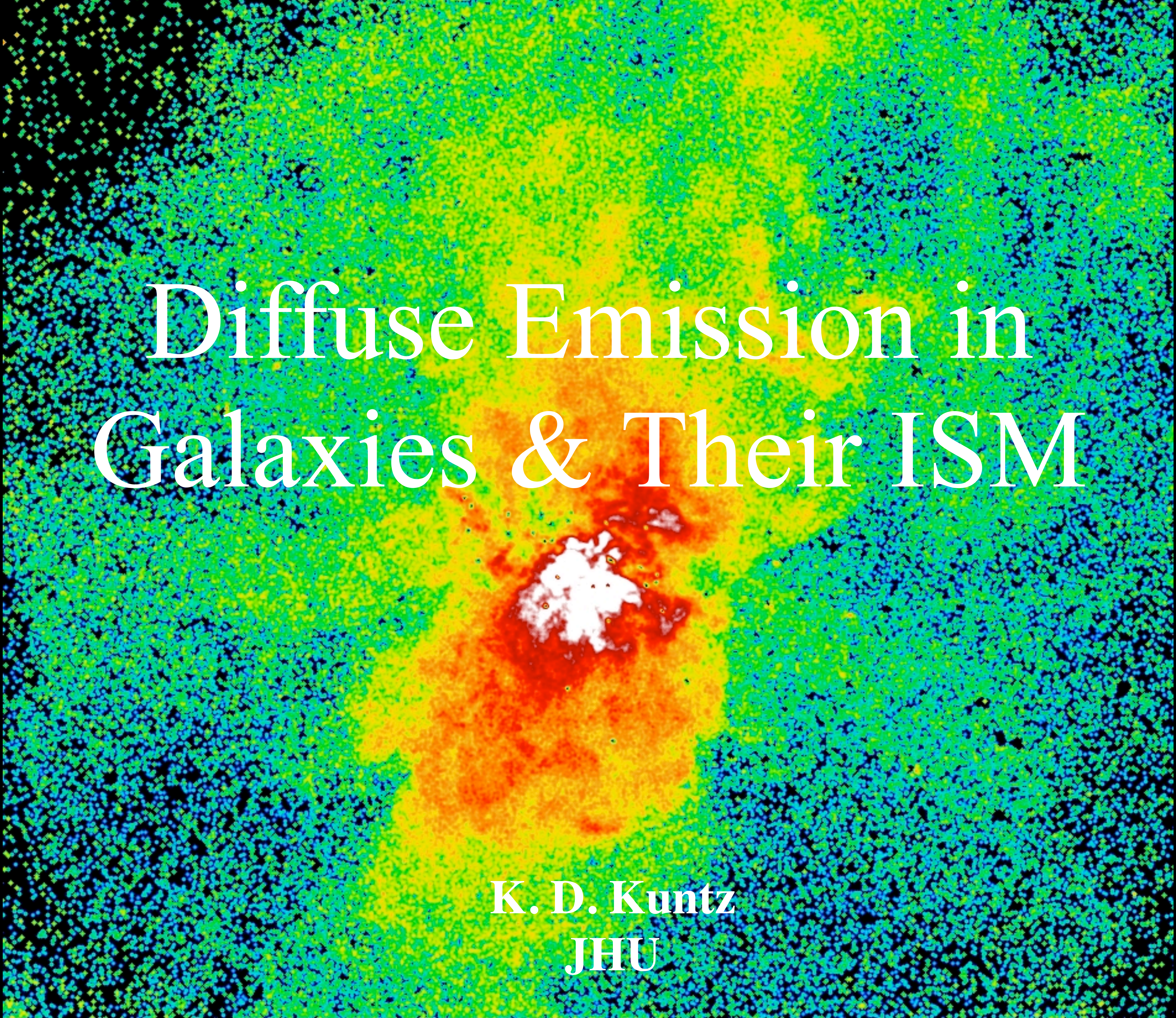


Diffuse Emission in Galaxies & Their ISM

K. D. Kuntz
JHU

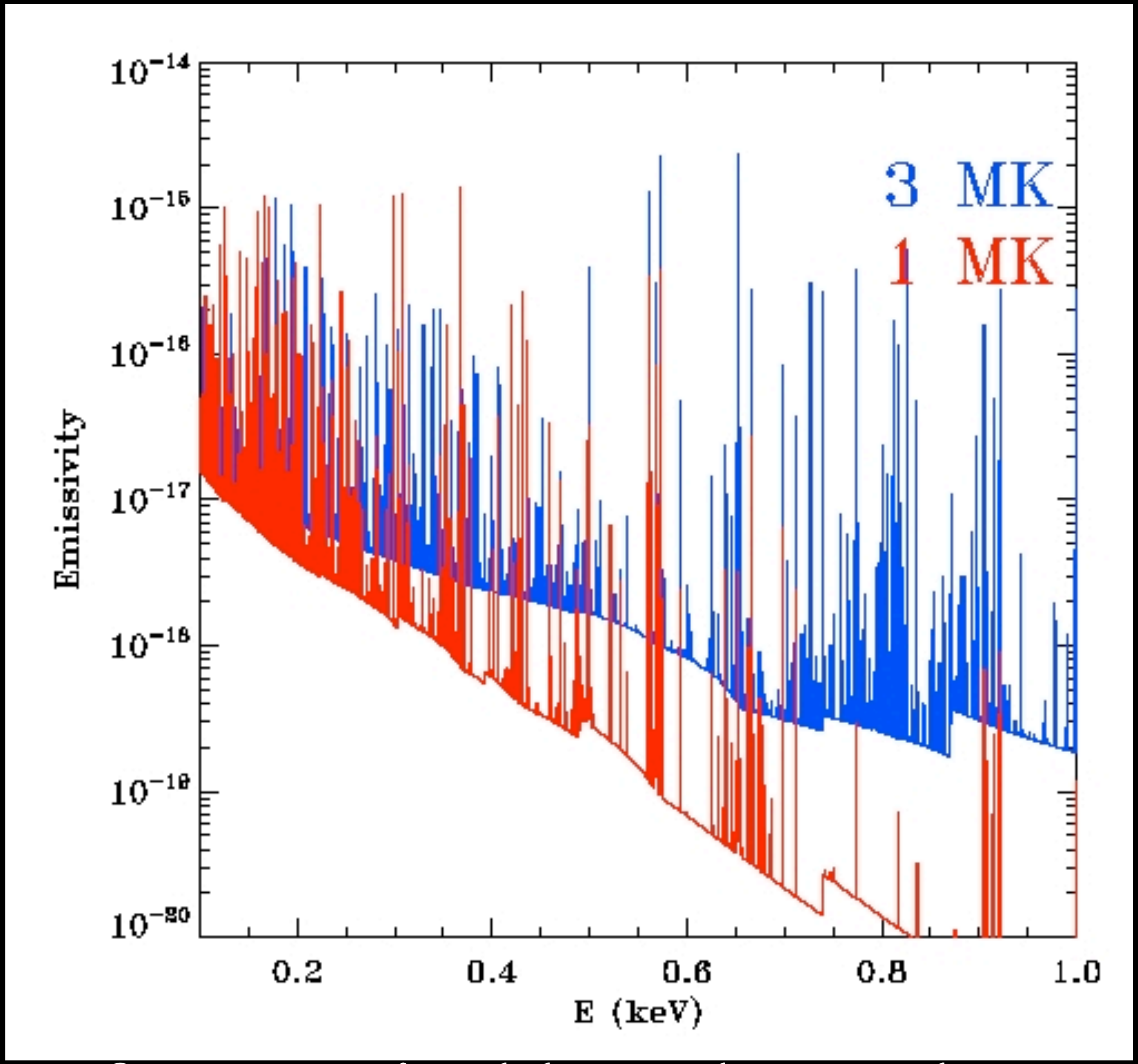
Reminders

Diffuse Emission = Thermal Emission (Usually)

As T increases ➙ Excite higher ionization states

➙ Higher ionization states dominated by higher E lines

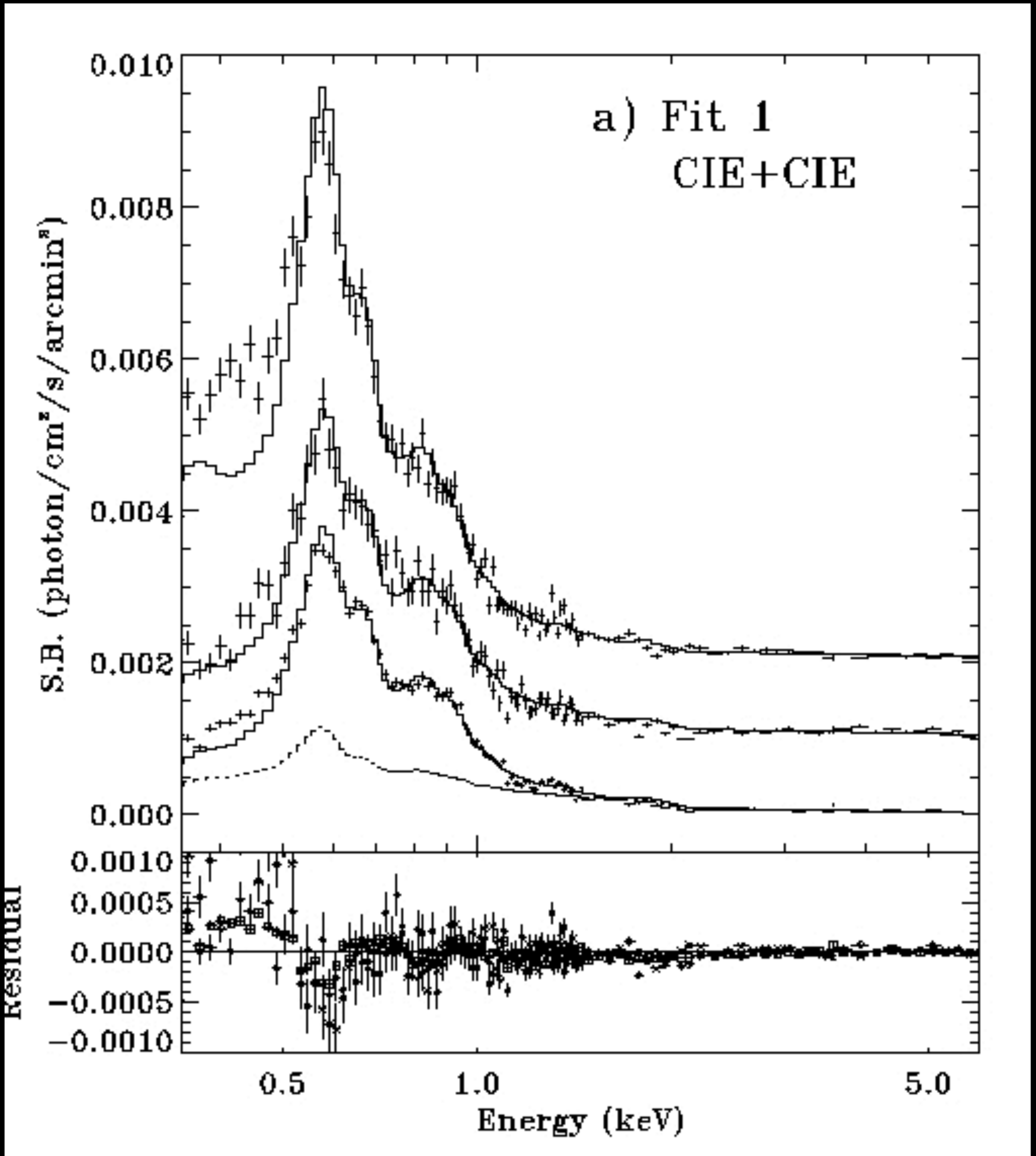
At CCD resolution, higher T ➙ higher cutoff energies



Bulk of emission from typical hot plasma has E<2 keV

What We Actually See

Due to spectral resolution abundances difficult to determine particularly for low temperature components



Reminders

Thermal Emission $\neq$ Collisional Ionization Equilibrium (CIE)

Non-Equilibrium Ionization (NEI): which NEI?

- under-ionized plasma: $T_e > T_{pop}$
  - typical of shocks
  - nei, vpshock in xspec
- over-ionized plasmas: $T_e < T_{pop}$
  - typical of adiabatically cooled gas
  - (there are no such models in xspec)

Boltzmann Eq:

$n_2/n_1 \propto \exp(X/kT_{pop})$

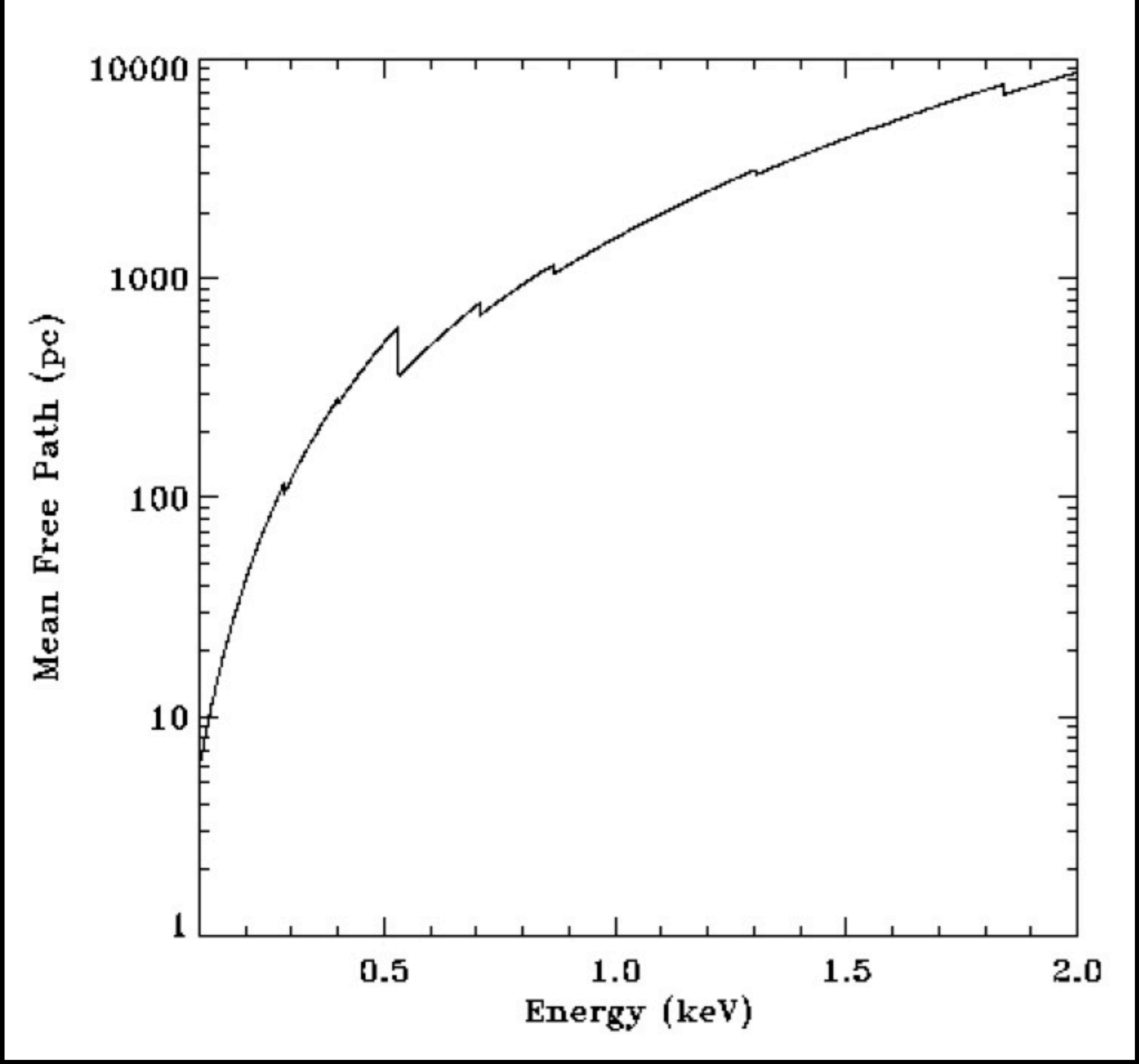
Reminders

Interstellar Absorption:

$$I=I_0\exp(\sigma N(H)) \text{ and } \sigma \propto E^{(-8/3)}$$

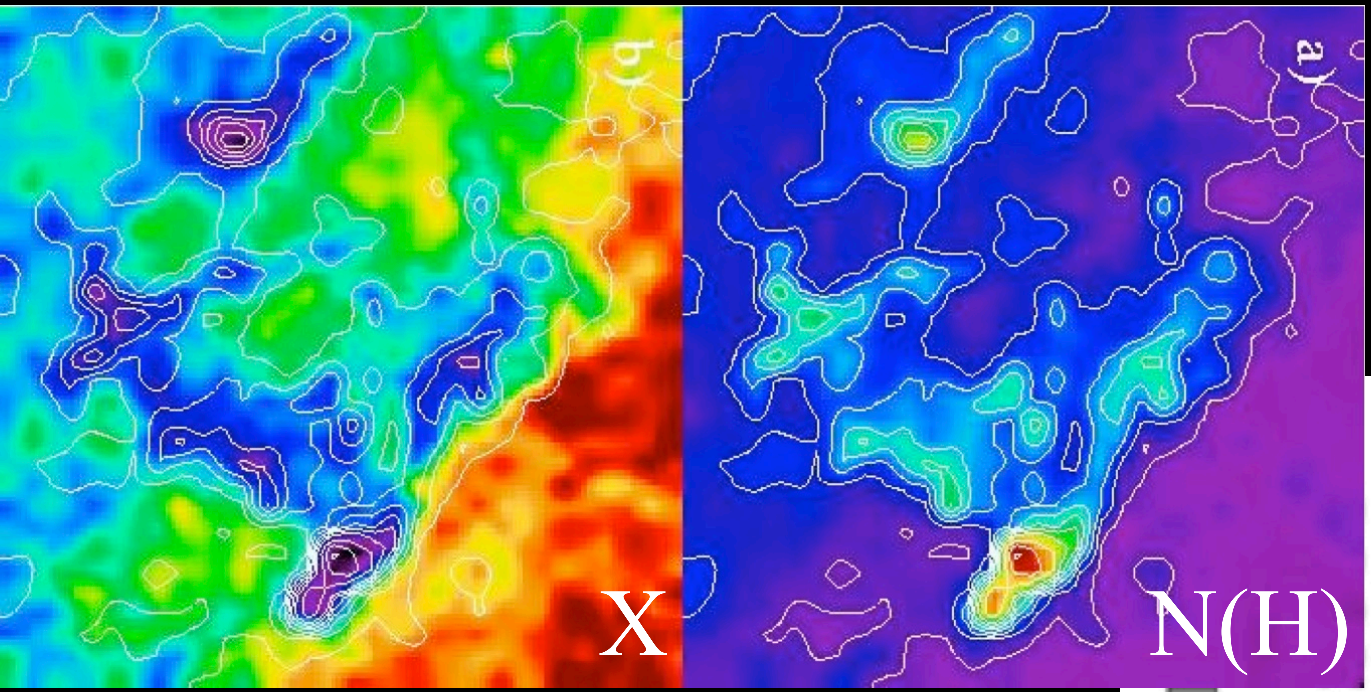
→ absorption produces bluing

Difficult to observe the Galaxy at $E \leq 1$ keV

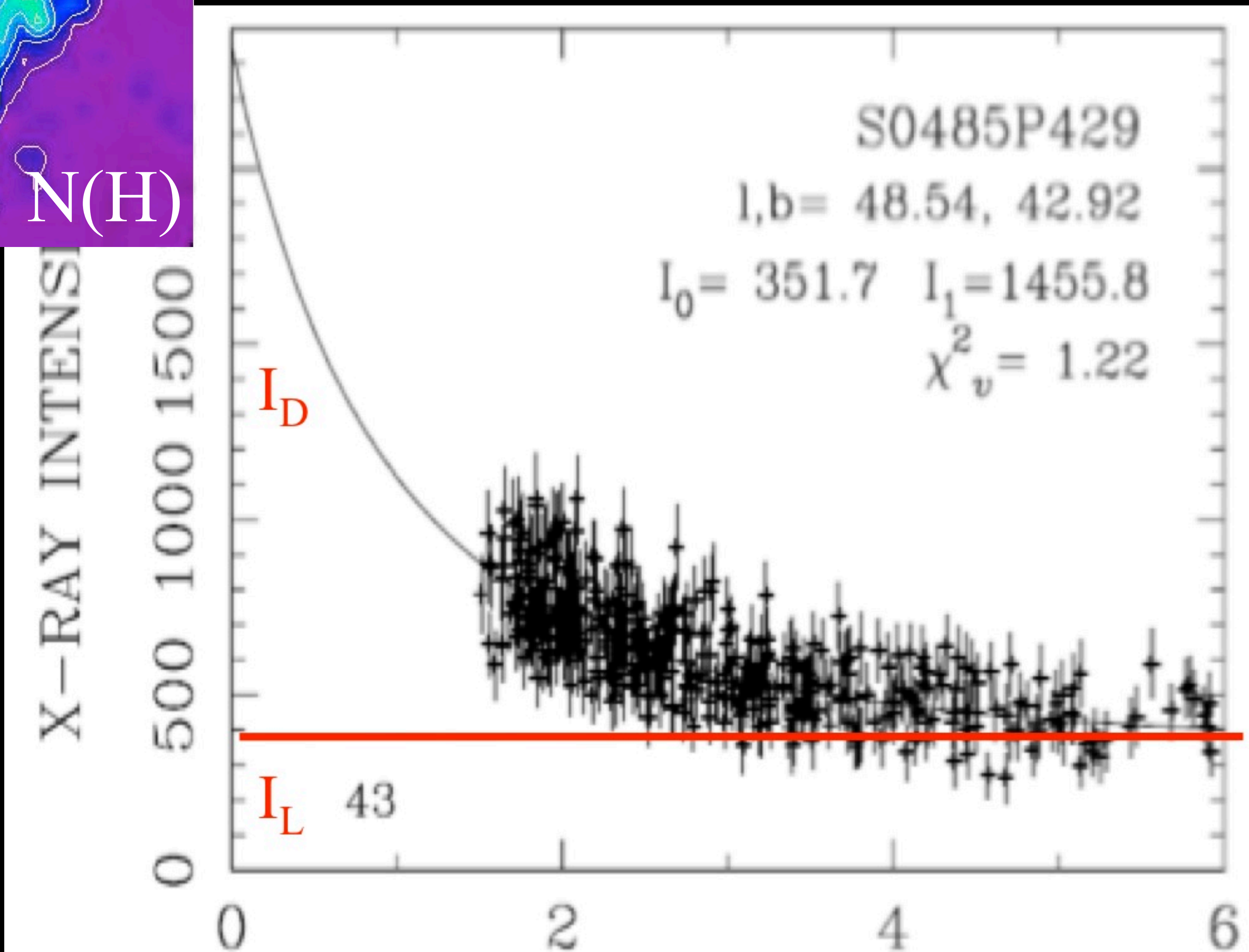


Reminders

If N(H) varies by large amounts over small regions one can use the anticorrelation to determine I_{local} & $I_{distant}$



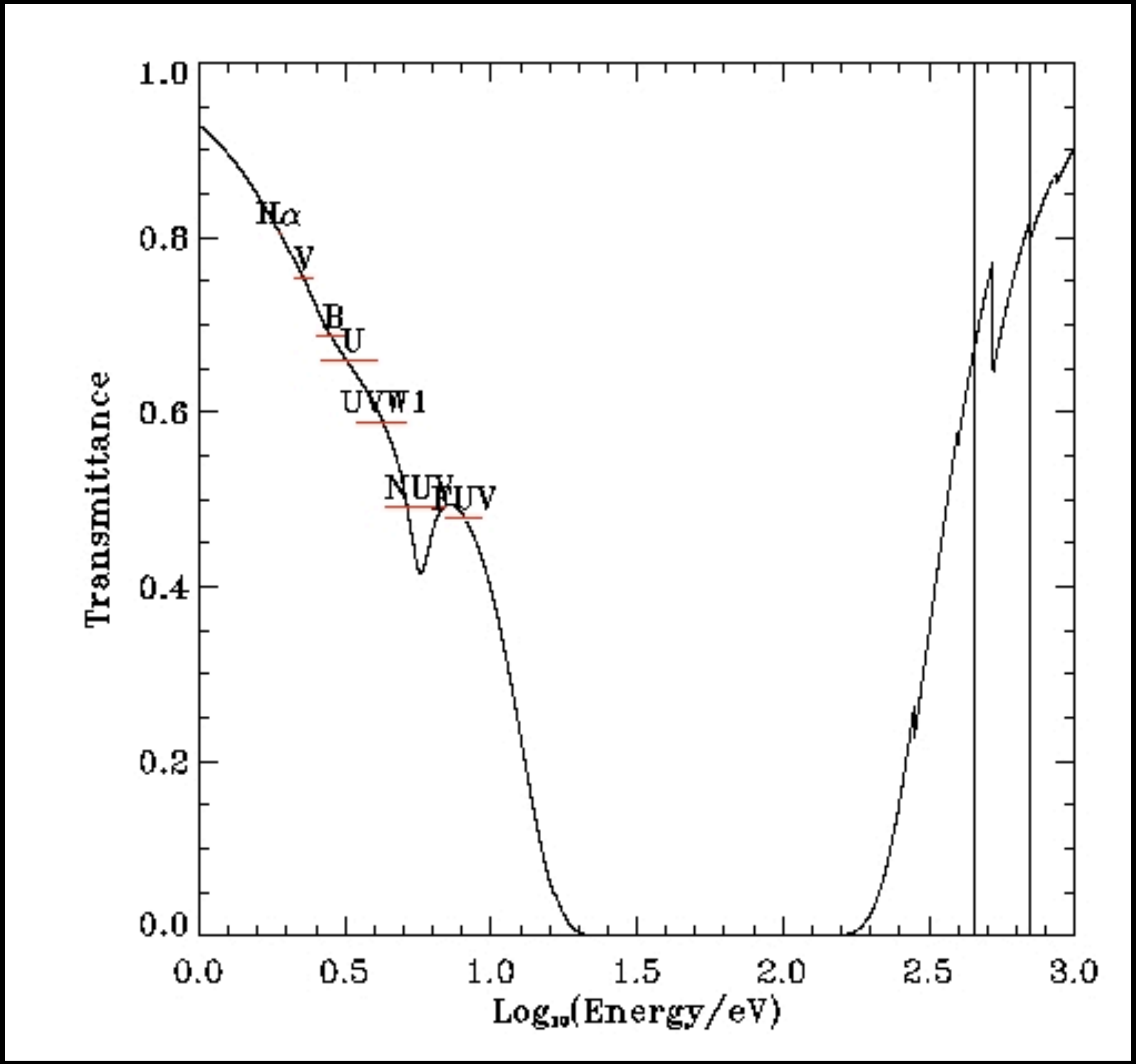
$$I_{obs}=I_L+I_D e^{(-\sigma n)}$$



Absorption can be your friend!

(Partial) Myth

That X-rays much much less absorbed than optical photons -
- It really depends upon the energy!



Diffuse X-ray Emission in Galaxies

Classic Justifications:

- X-ray Emission traces the most energetic part of the ISM
  - Assumed to be produced mostly by SNR
- Mechanical energy “sculpts” the cooler components
- Hot gas contains the newly create metals
- If sufficiently energetic hot gas can escape galactic disk (through galactic chimneys)
  ➙ extended hot halo ➙ inhibits gas infall
    ➙ quenching star formation ➙? galaxy evolution
- If even more energetic can escape galaxy
  ➙ enriches the IGM and the WHIM
    ➙? why zero-metal gas does not exist
- Study of low-z systems tells us about high-z systems

Diffuse X-ray Emission in Galaxies

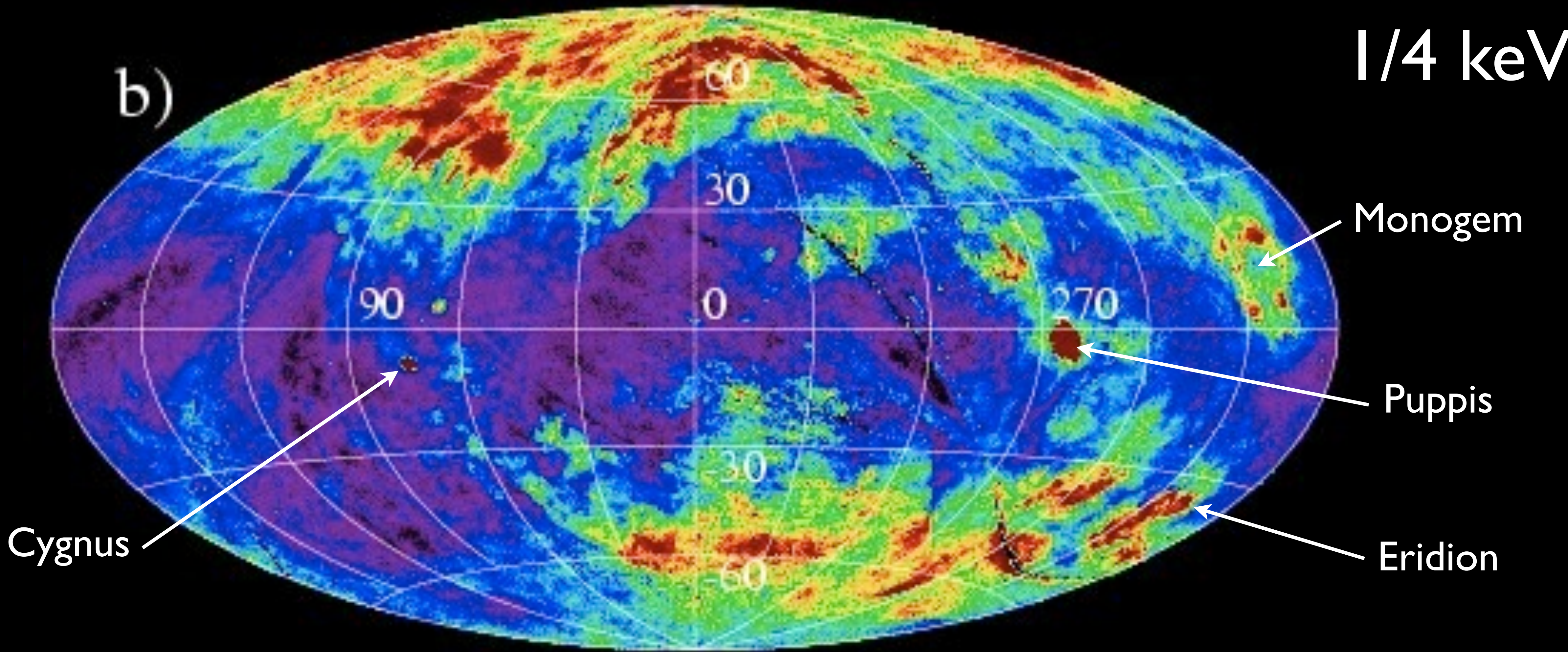
Classic ISM Questions:

- What are the main sources of X-ray emission?
- How much hot gas is there (Mass? or Energy?)

- What is the life-history of the hot gas?
  - Where does it go?
  - How quickly does it cool?
- Under what conditions does it escape?

Questions that we can address:

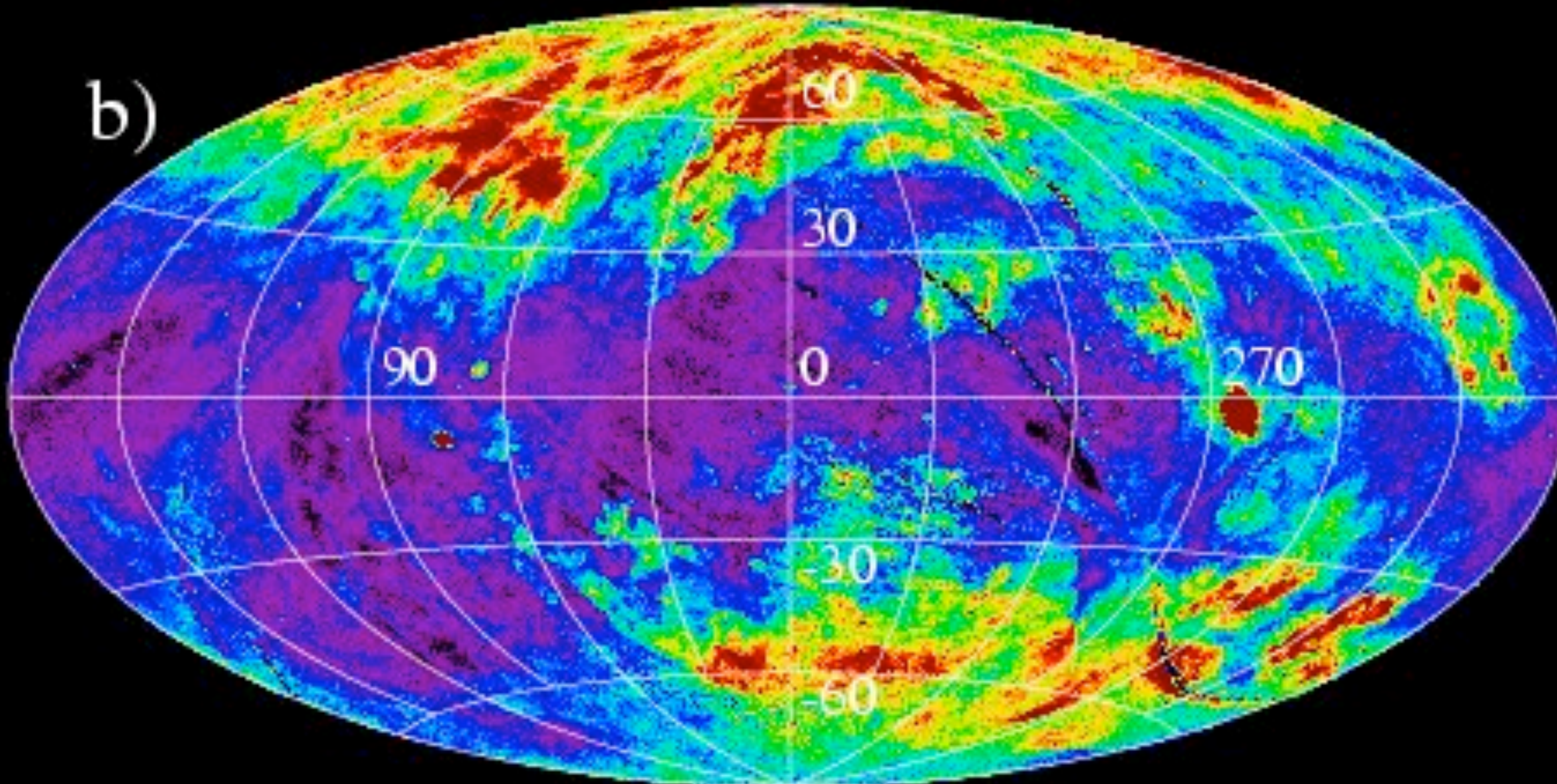
- What are the sources of the X-ray emission?
- How much is due to hot gas?
- What is the physical state of the gas?
  - (Need to know in order to calc. Mass and Energy)



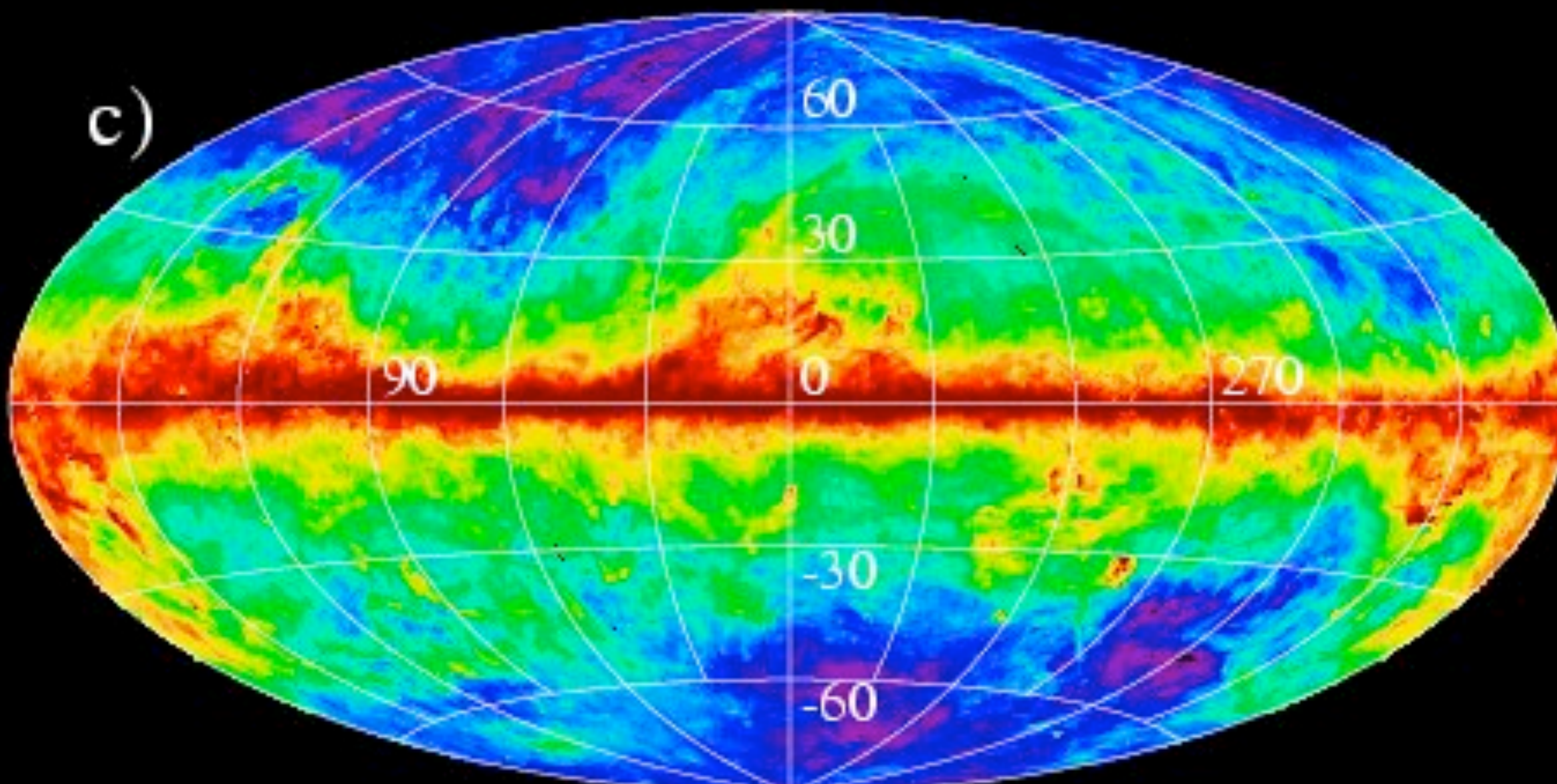
What do we see?

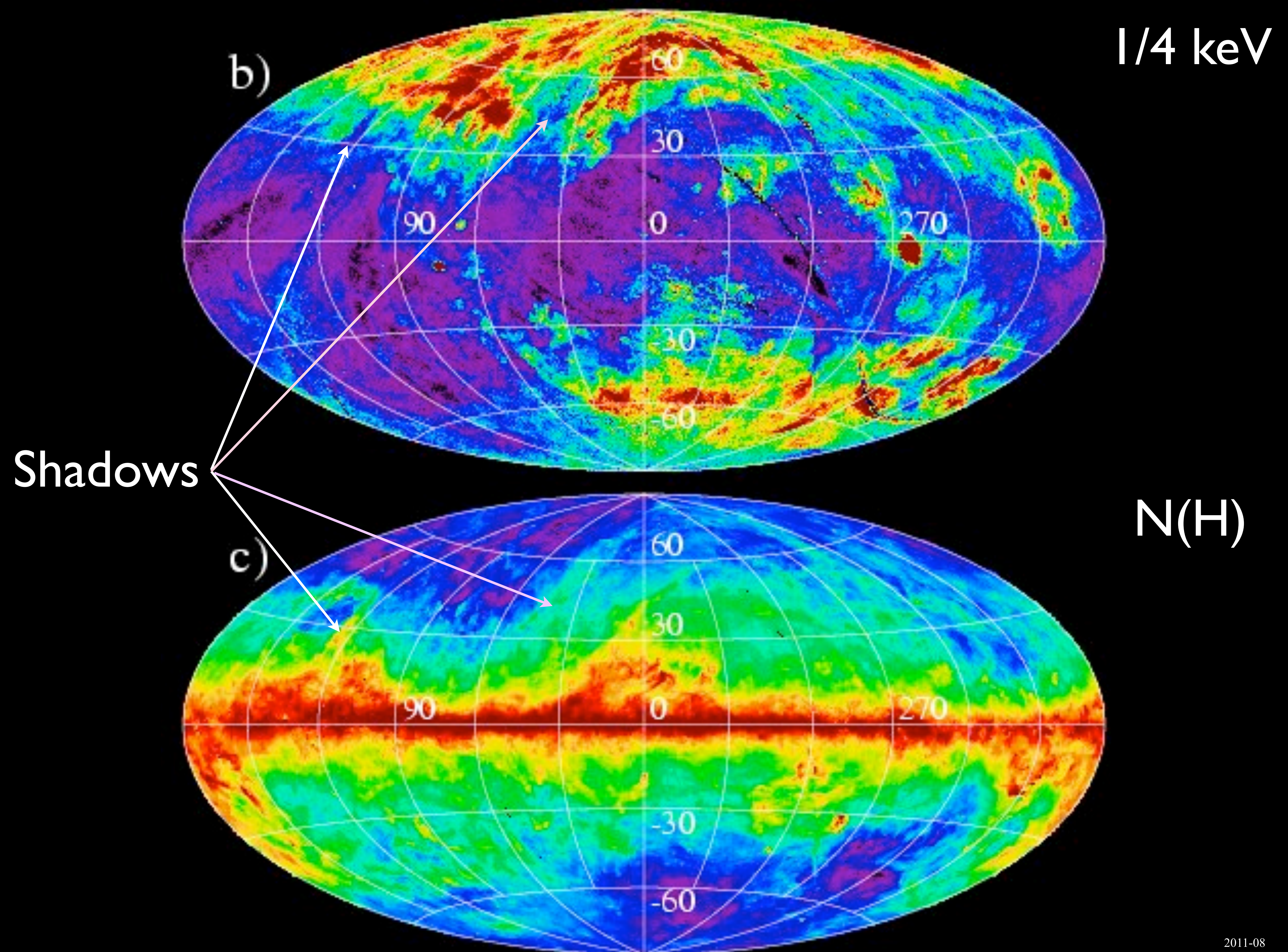
- SNR mostly in Galactic plane
- Shadows at high Galactic latitude
  - ➙ bright emission is the Galactic Halo
- The flux is not zero in the Galactic plane
  - ➙ significant emission nearby (R<1 kpc)

1/4 keV



N(H)




1/4 keV
b)
60
30
90
0
270
-30
-60
Shadows
N(H)
c)
60
30
90
0
270
-30
-60

Local Hot(?) Bubble

At 1/4 keV, the mean free path ~ 100 pc yet

- we see emission in all directions

➙ must be a source of emission nearby

- look at a nearby, dense molecular cloud
- from band ratios and spectral fitting kT~0.09 or T~10^6 K (emission almost insignificant at 3/4 keV)
- from T and R~100pc ➙ gas likely in thermal equilibrium

➙ observed flux as f(direction) ∝ pathlength (use variation in N(H) to seperate local and distant gas)

- region of hot gas ~ region lacking neutral gas

Local Hot(?) Bubble

At 1/4 keV, the mean free path ~ 100 pc yet

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(use variation in N(H) to seperate local and distant gas)

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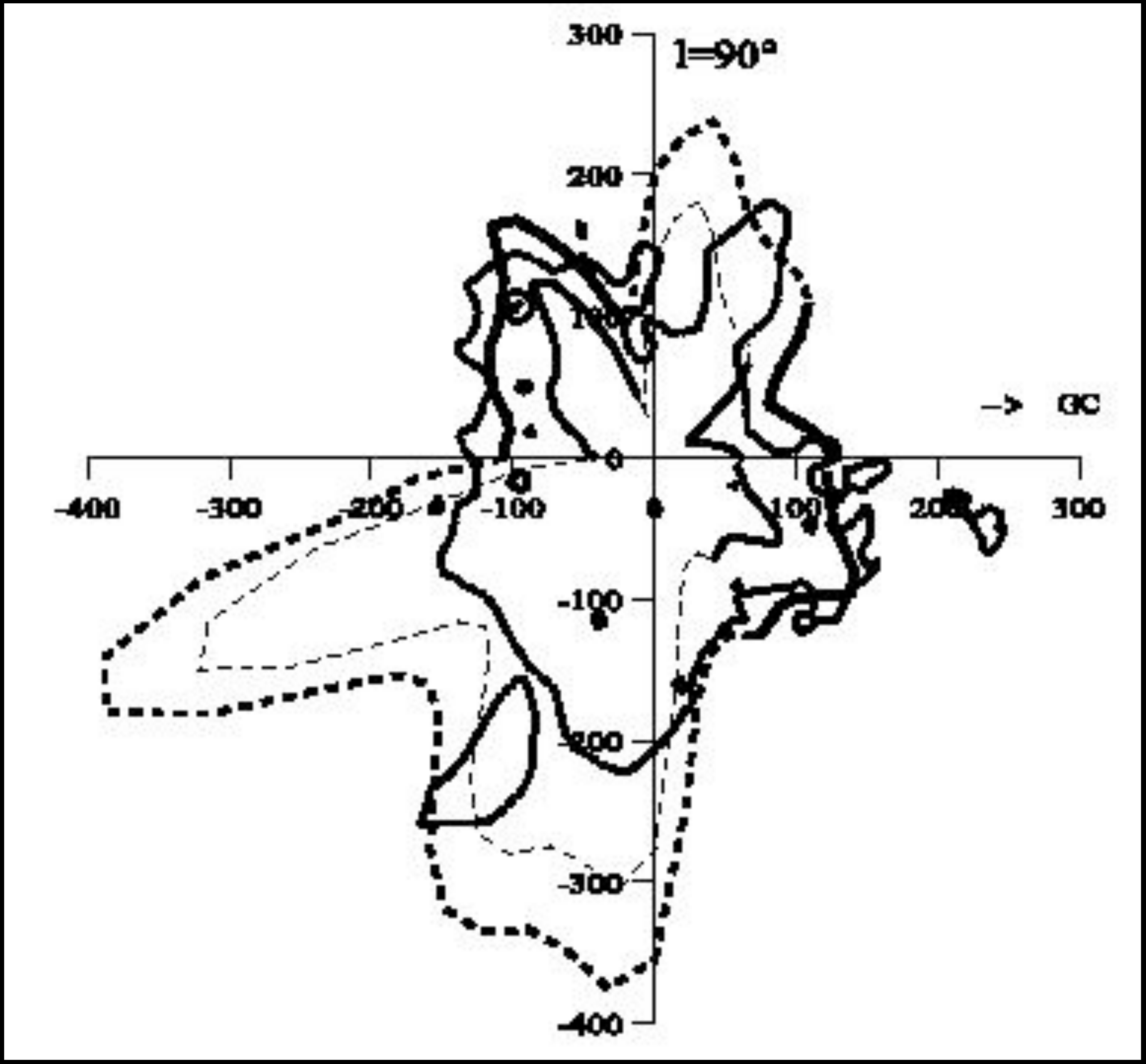


Local Hot(?) Bubble

Comets were found to emit X-rays! through charge exchange:

$$H+O^{+7} \rightarrow H^{+}+O^{+6}+\nu$$

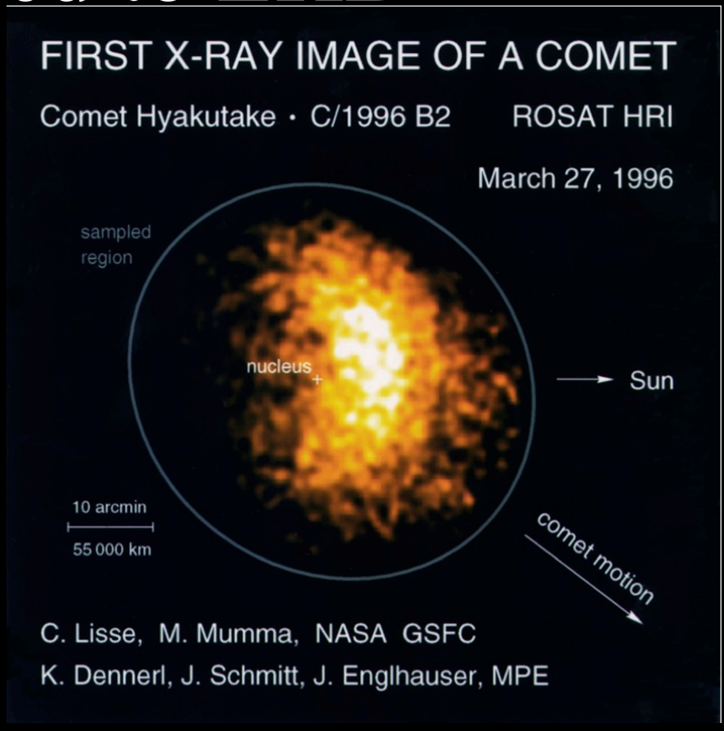
So all neutral material in solar system should emit!

ROSAT experienced a time-variable background (LTEs)

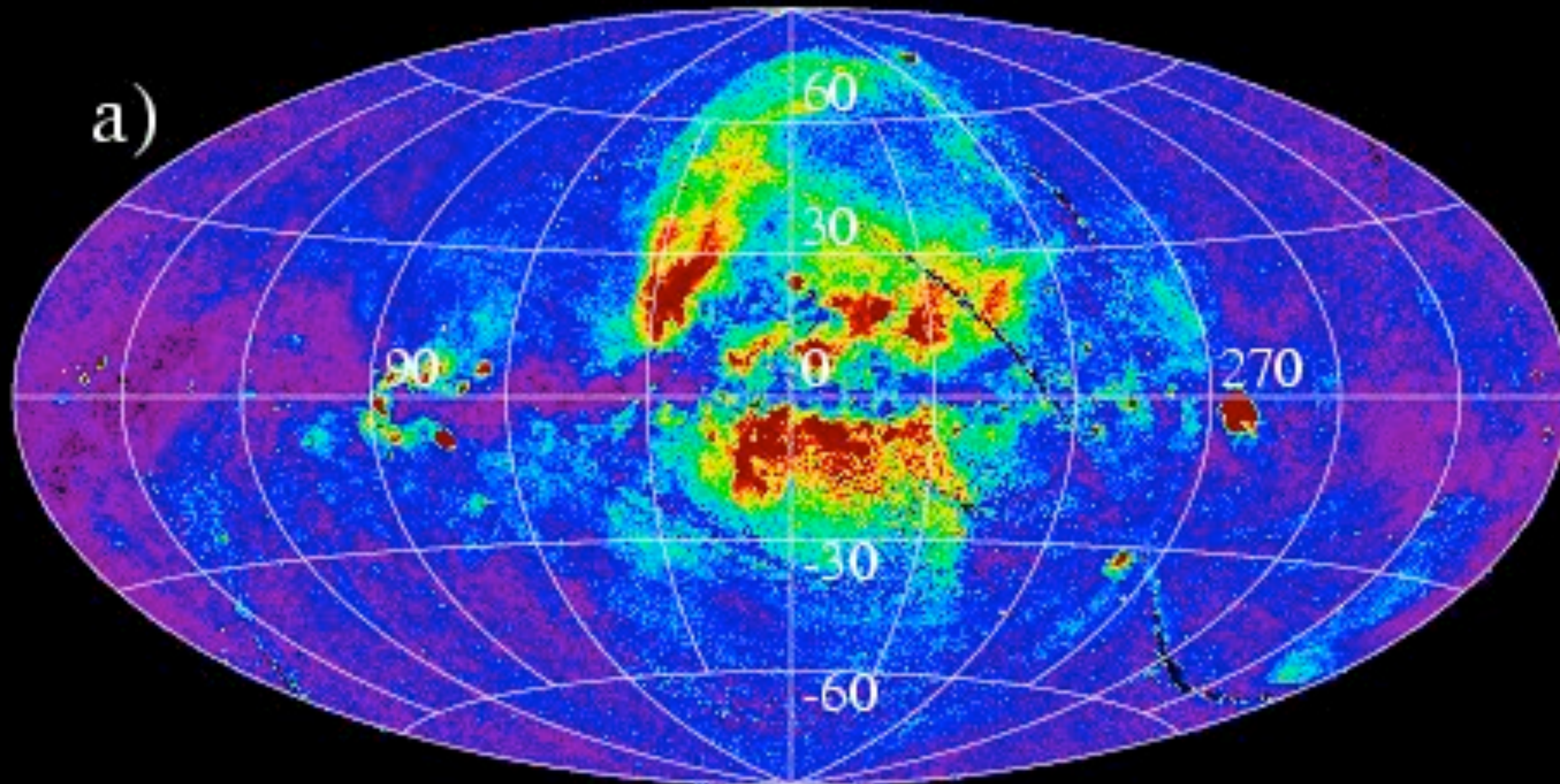
- found to be correlated with the solar wind
- due to interactions of solar wind with
  1) ISM flowing through solar system
  2) the exosphere
- most of this contamination removed from RASS but...
- some portion remains and incorrectly attributed to LHB

How much of the LHB remains?

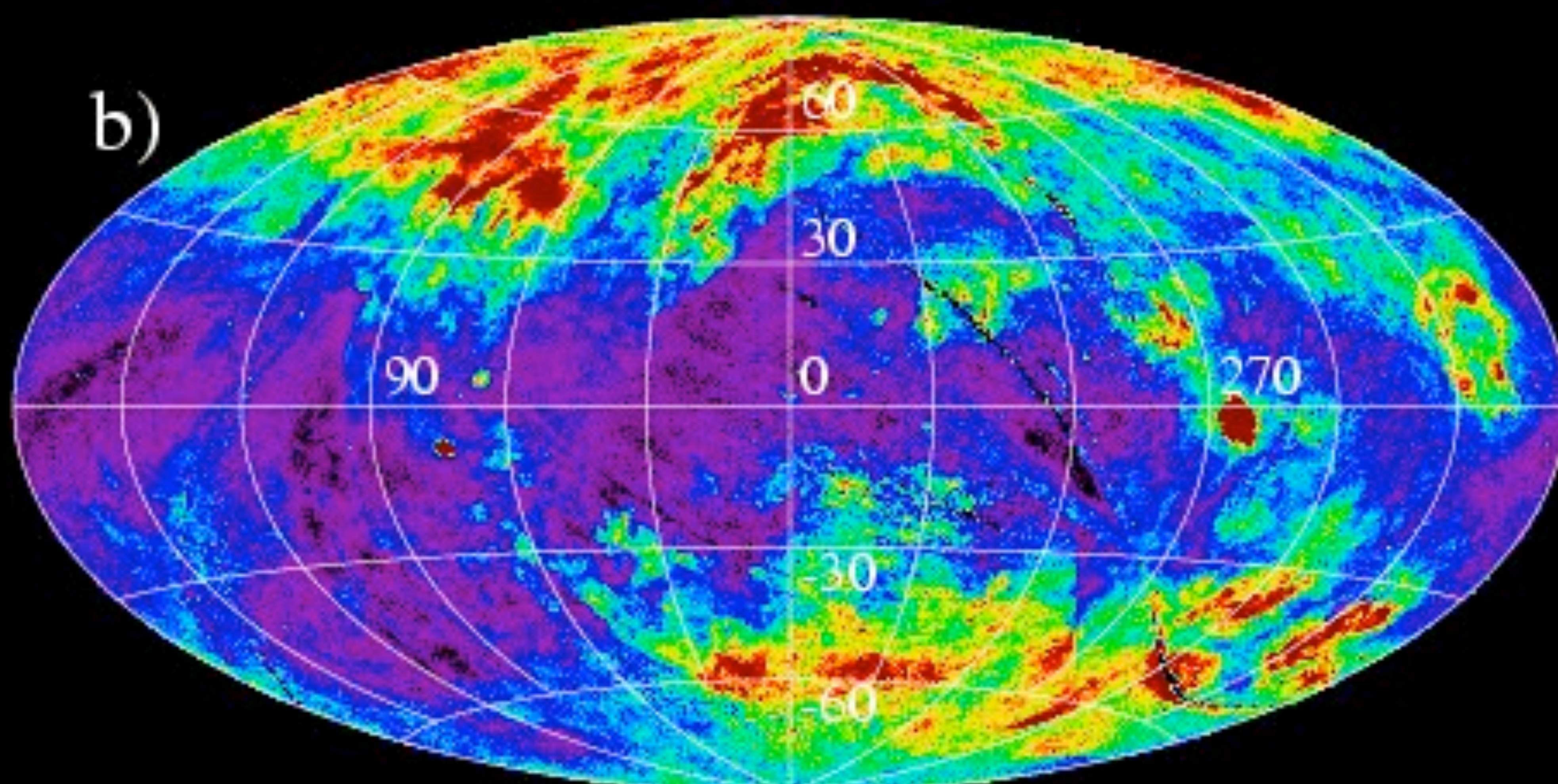
- about half of previous estimates



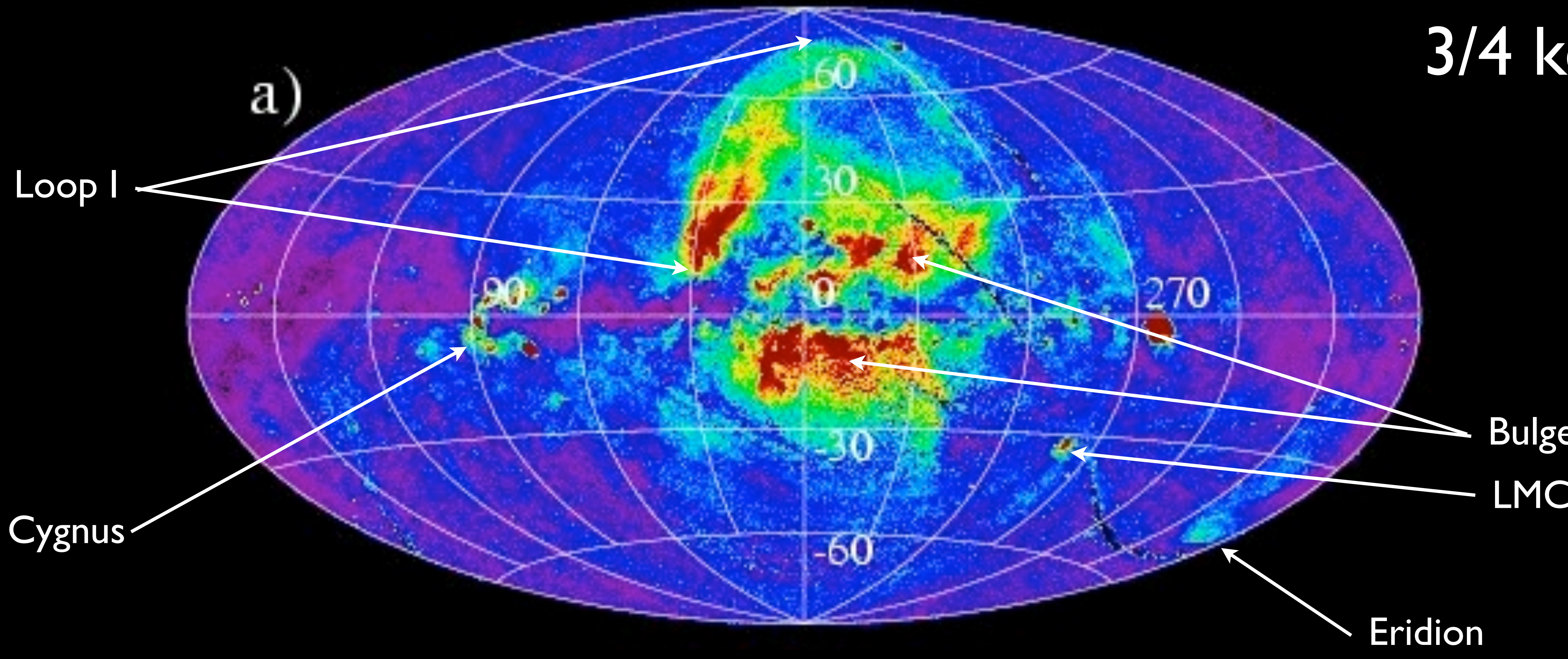
3/4 keV



1/4 keV

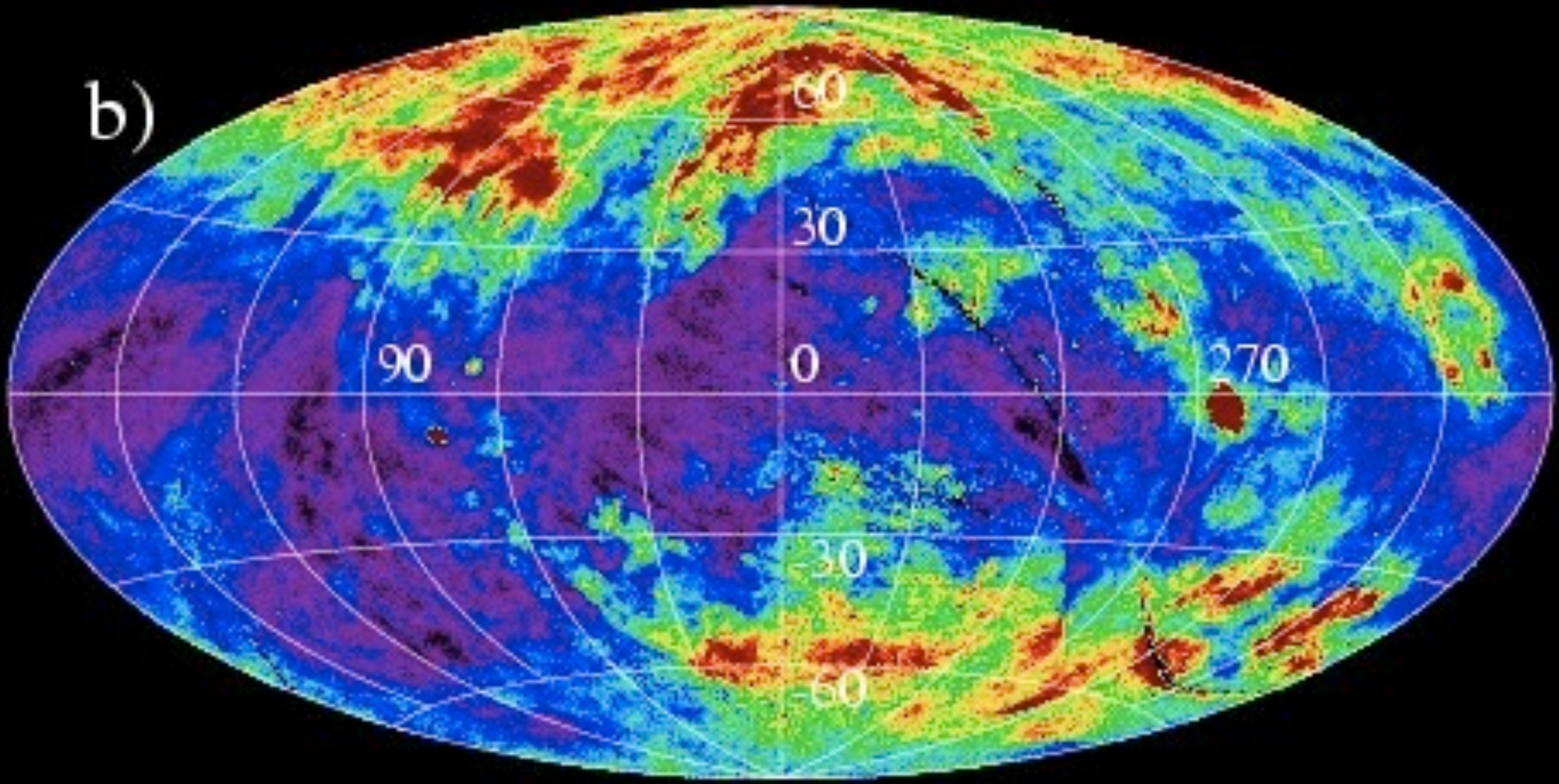


3/4 keV



What do we see?

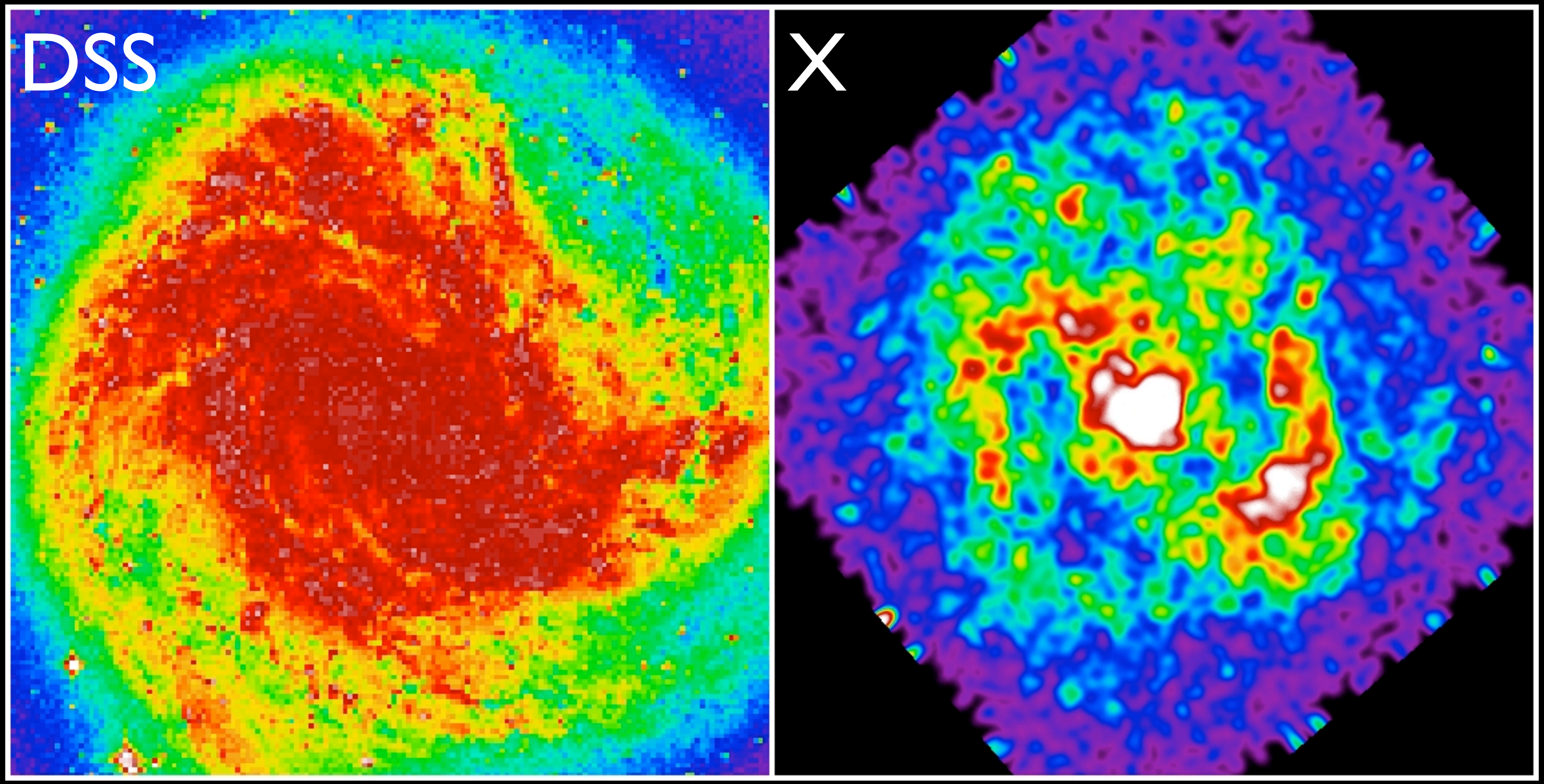
- Superbubbles
- Galactic bulge
- Some shadows in Galactic plane
  (but not enough to account for absorption of extragalactic emission due to AGN: the classic “infill problem”)



In the Galaxy

- generally impossible to determine R to diffuse emission
  - ➙ impossible to measure total Mass or Energy
- absorption by Galactic disk
  - ➙ see only the solar neighborhood
  - ➙ very biased view of the Galaxy

What's In A Galaxy?



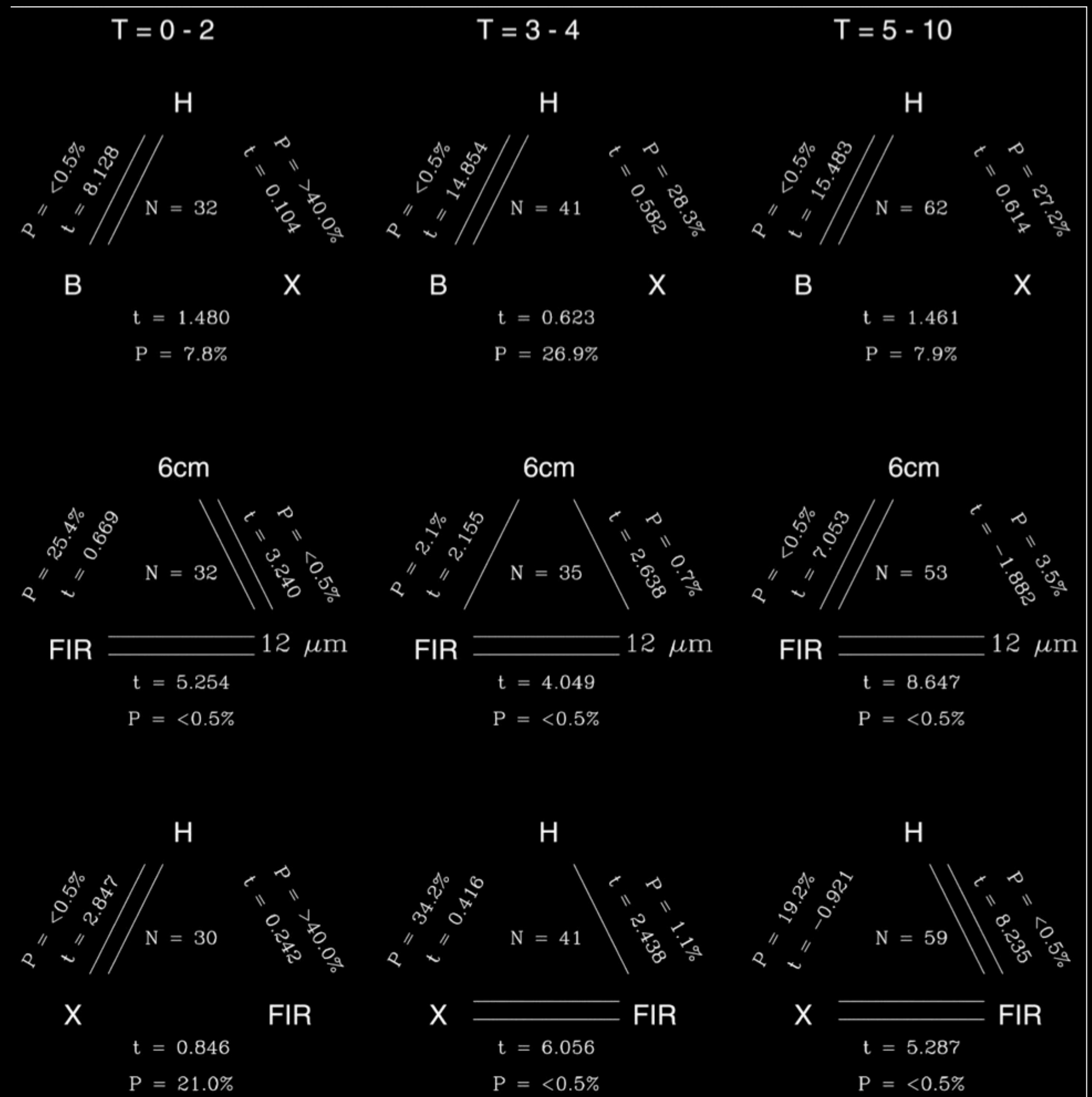
In Nearby Galaxies
- everything at the same distance
- relative locations and sizes obvious, but
- lower spatial resolution ➙ more confusion
  ➙faint sources "fade" into diffuse emission

What's in a Galaxy?

SNR
Star-formation Regions (bubbles & super bubbles)
Non-localized Diffuse Emission
Unresolved Stars (stellar coronae)
Unresolved X-ray Binaries
Galactic bulges
Galactic halo - thick disk (?)
Galactic halo - spherical (Spitzer Corona)

Which of these things are the important ones?

Shapley&Fabianno



Sab Scd

Early type spirals correlated with K-band ➙ mass

➙ dominated by stellar emission and/or halo

Late-type spirals correlated with FIR/Radio ➙ SFR

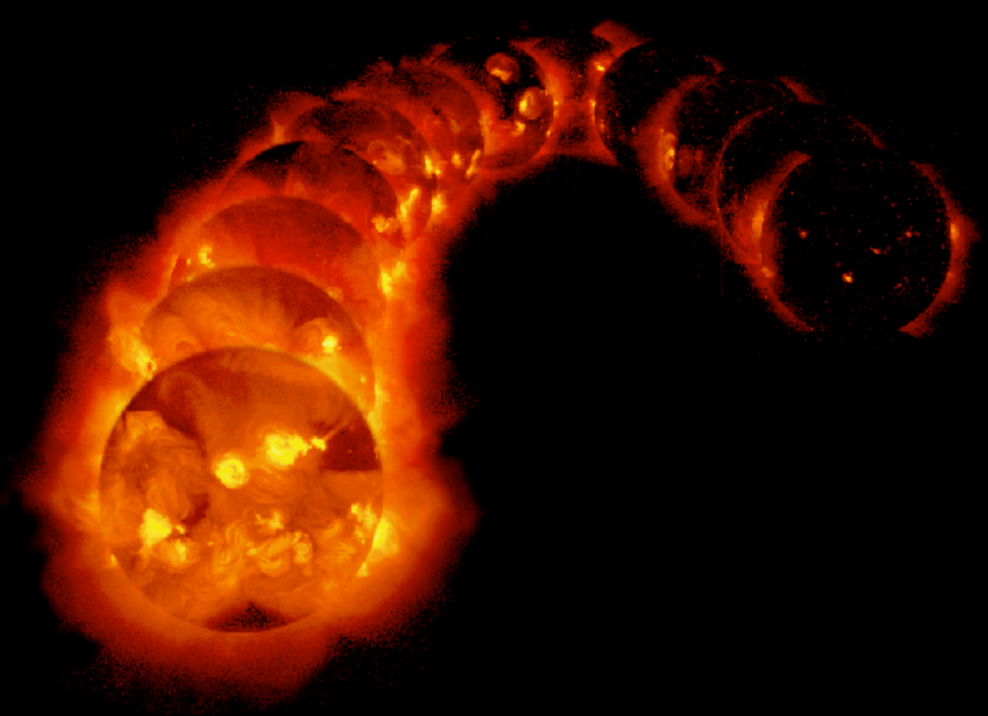
➙ dominated by star-formation (SNR, SFR, bubbles, etc.)

What's in a Galaxy?

<u>Early-type Spirals (Sa-Sb)</u>

Bulge dominated
Redder
More massive
Lower star-formation rate

X-rays from stars
→ X-ray dim
(except for bulges)



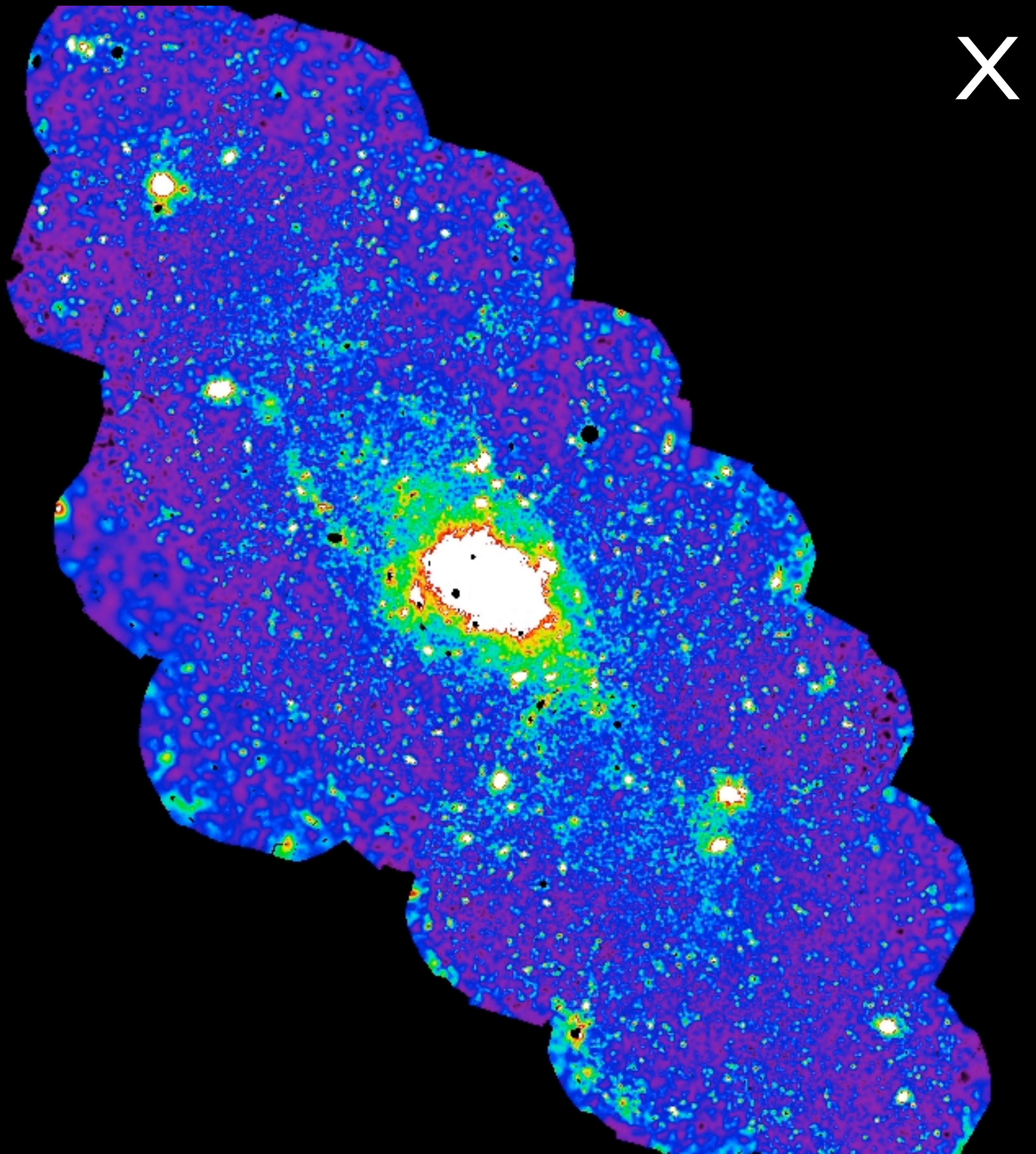
<u>Late-type Spirals (Sc-Sd)</u>

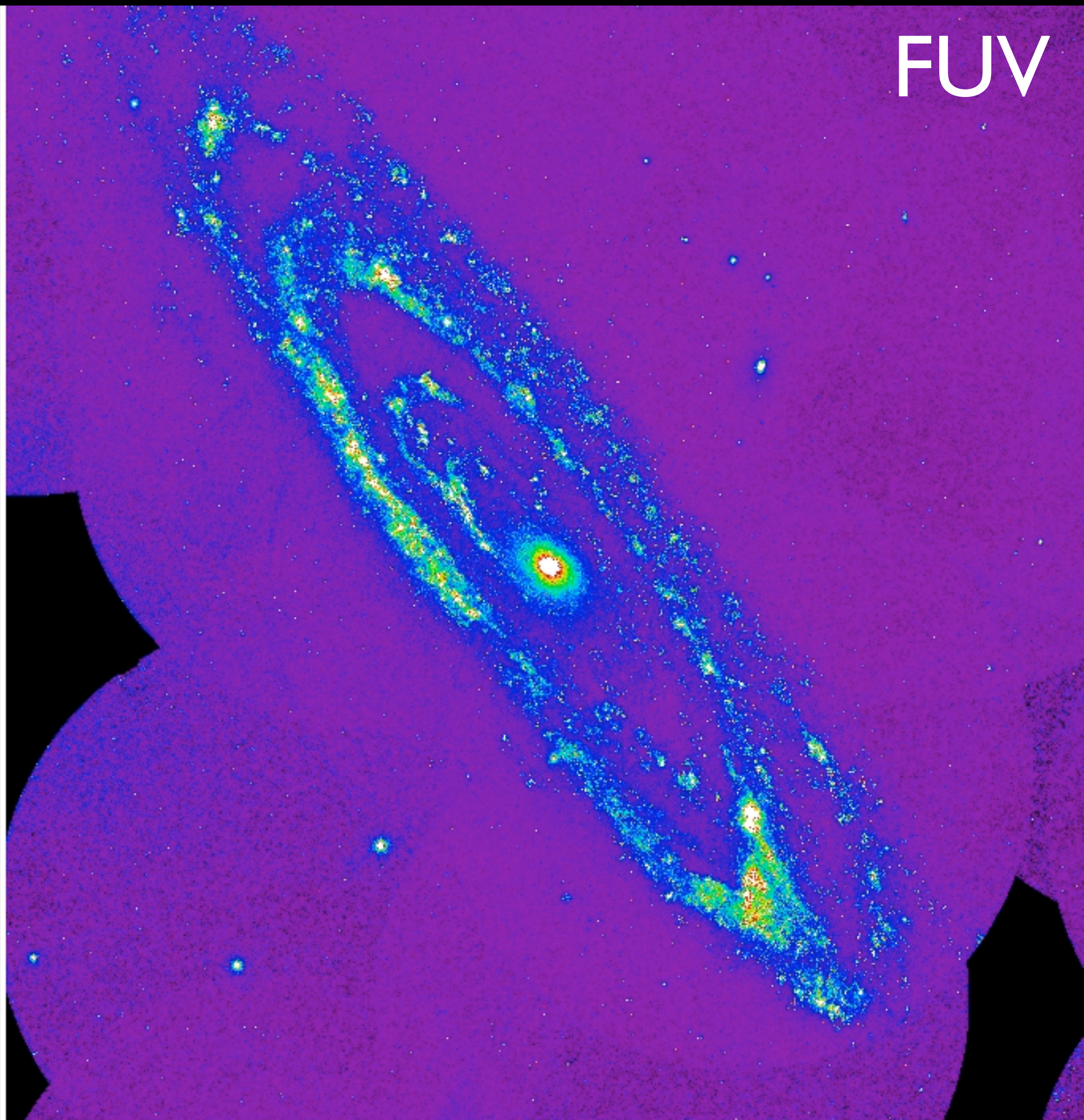
Disk dominated
Bluer
Less massive
Higher star-formation rate

X-rays from star-formation
→ X-ray bright

Early vs. Late

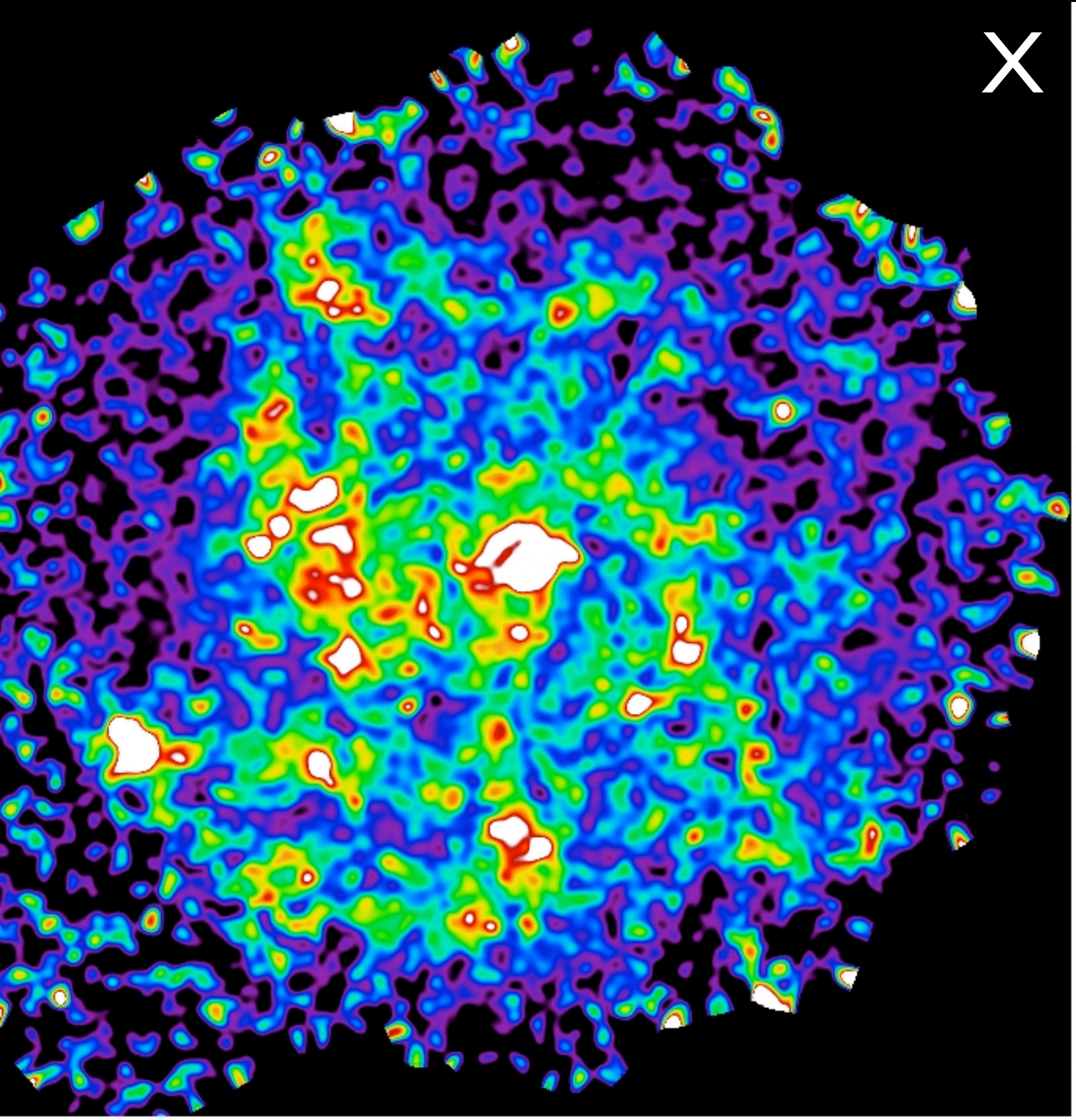
Early type (Sab) spiral M31
- bulge dominated
- disk nearly invisible

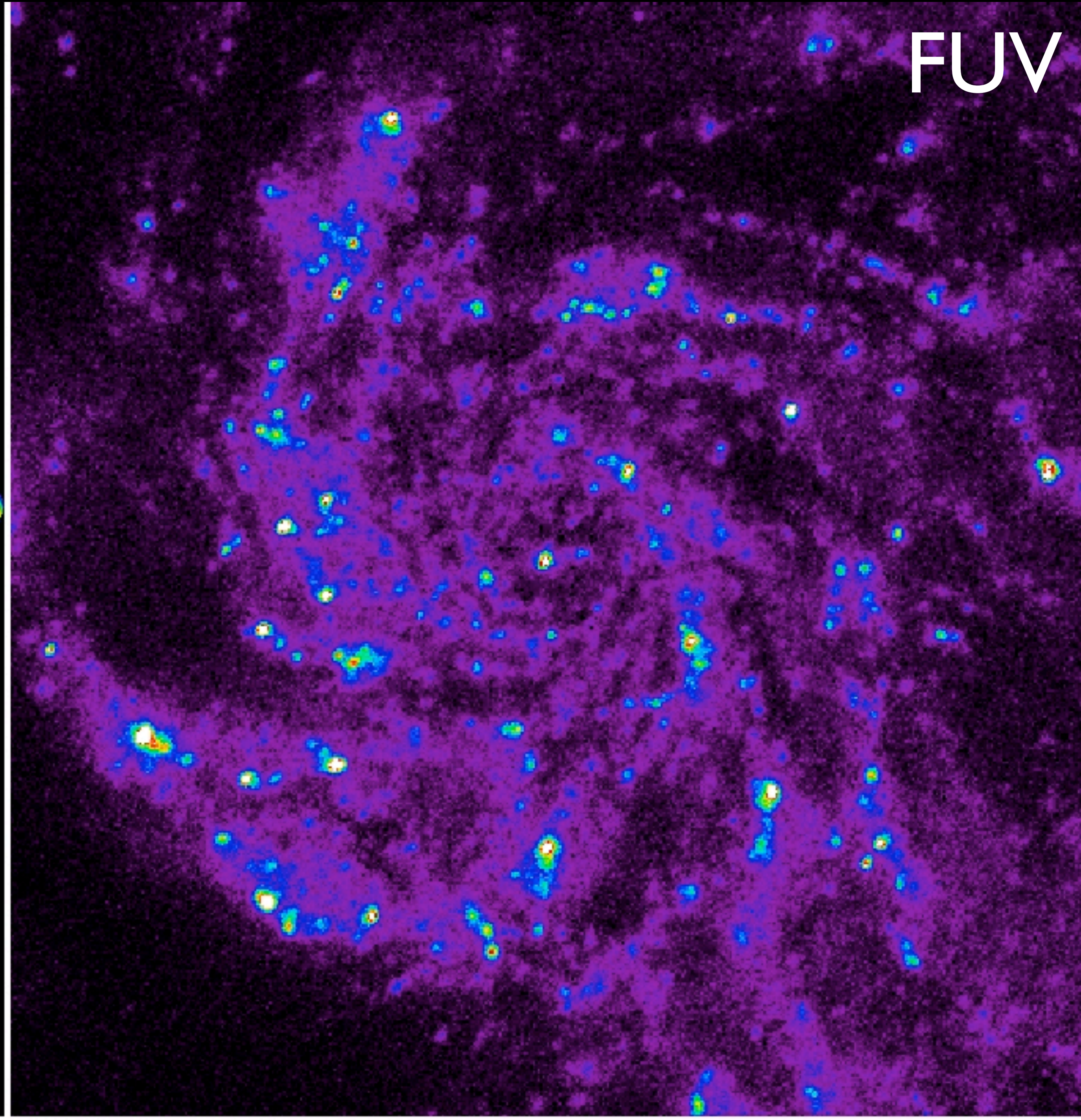




Early vs. Late

Late type (Scd) spiral M101
- bulge?
- disk emission, strong, traces the FUV (star-formation)





What's in a Late-Type Spiral Galaxy?

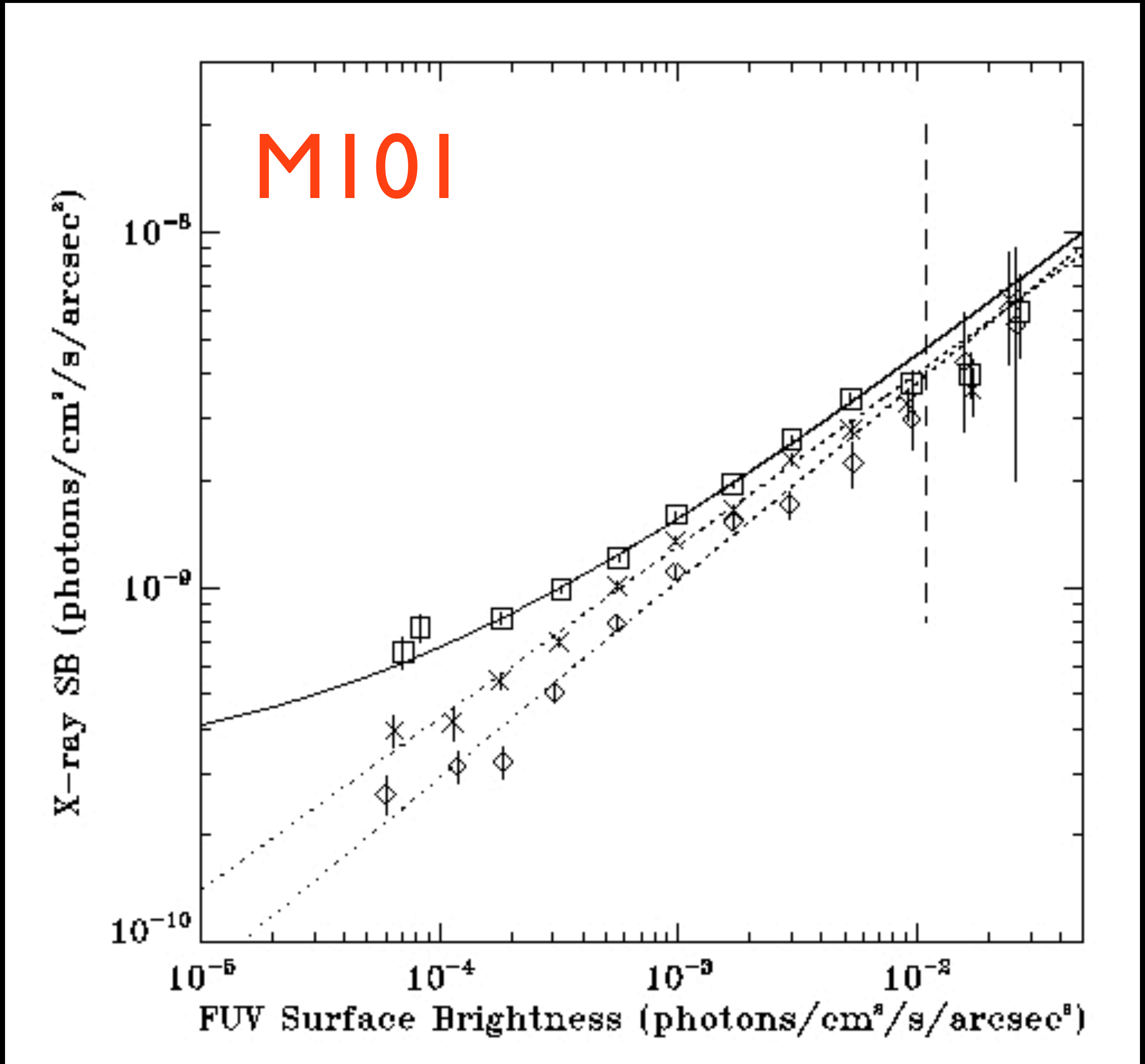
The bulk of the emission is correlated with the FUV emission

→ bulk of emission is due to star-formation.

Correlation is not linear (as expected!)

Approximately 5% of emission not due to star-formation

→ local and strength suggests due to stars



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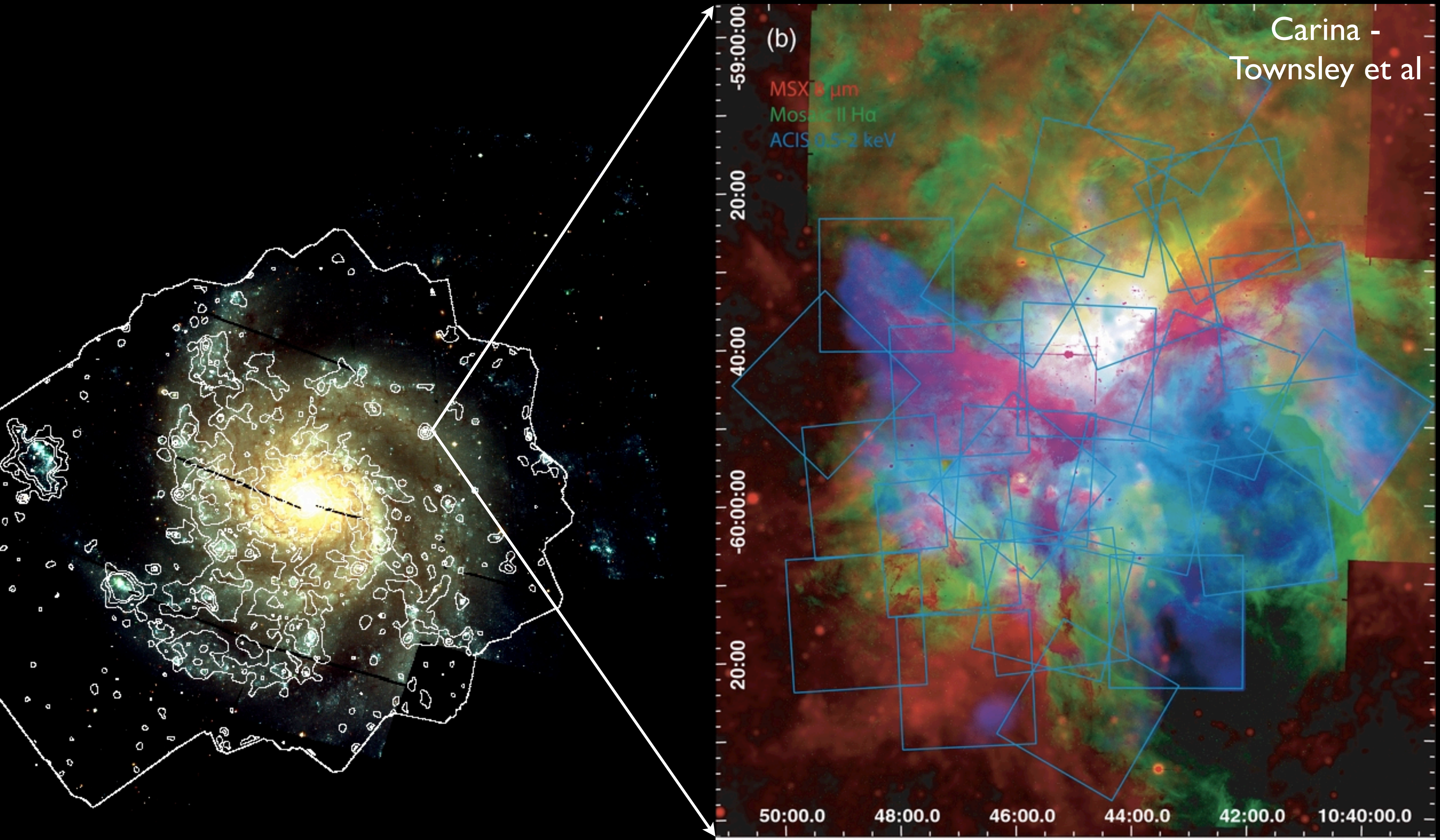
The bulk of the emission is due to star-formation.

But what does that mean?



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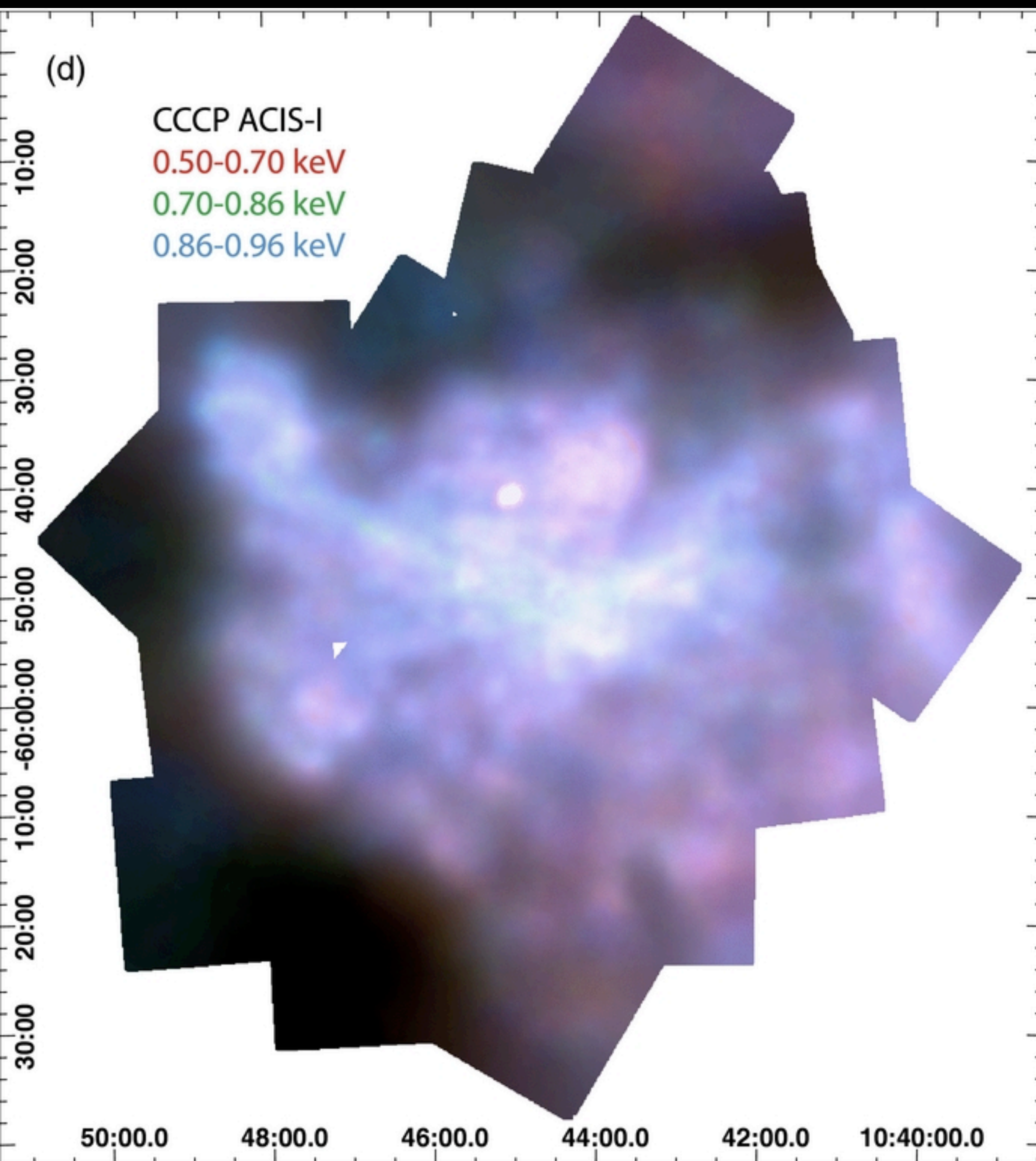
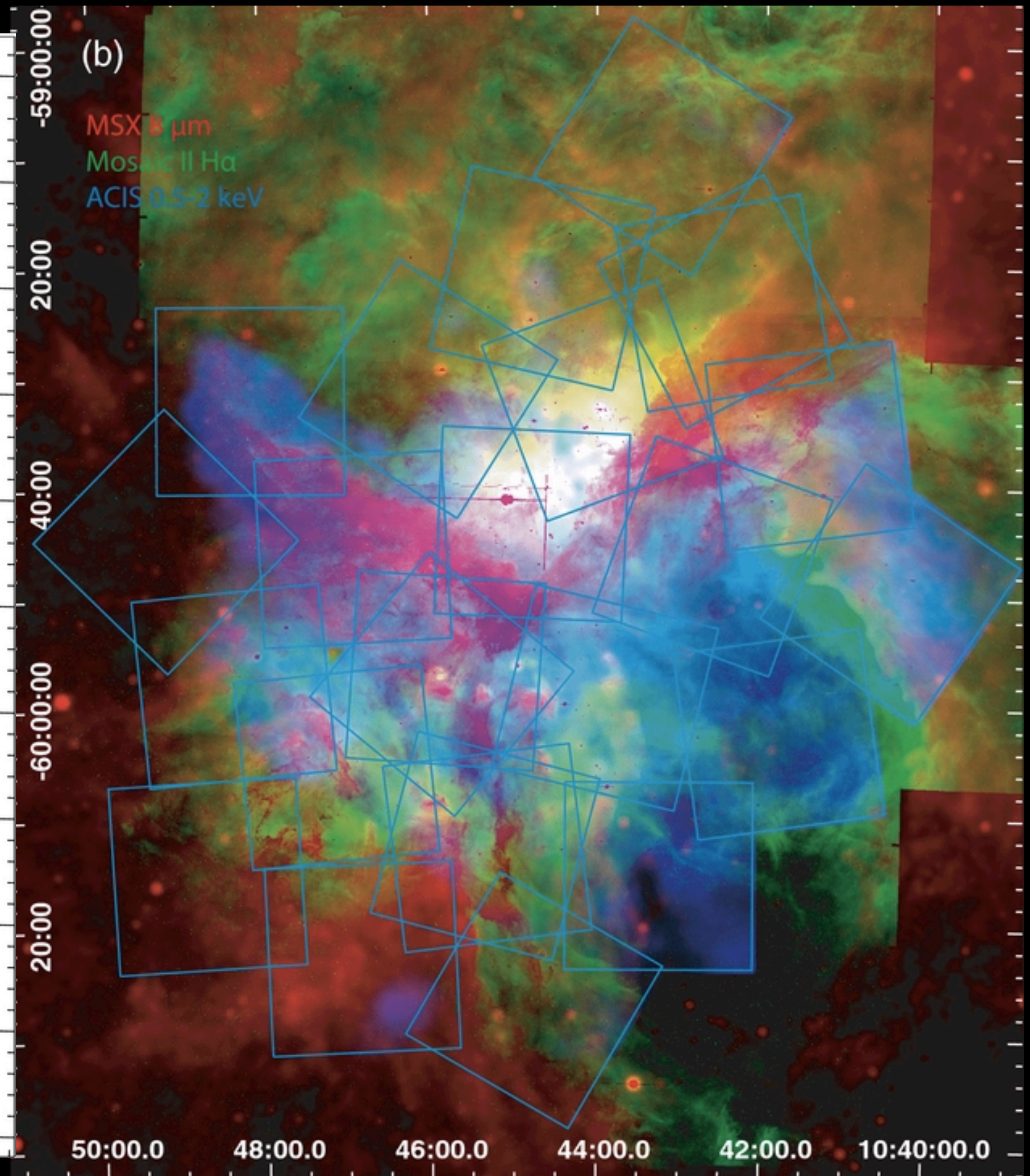




What's in a Late-Type Spiral Galaxy?

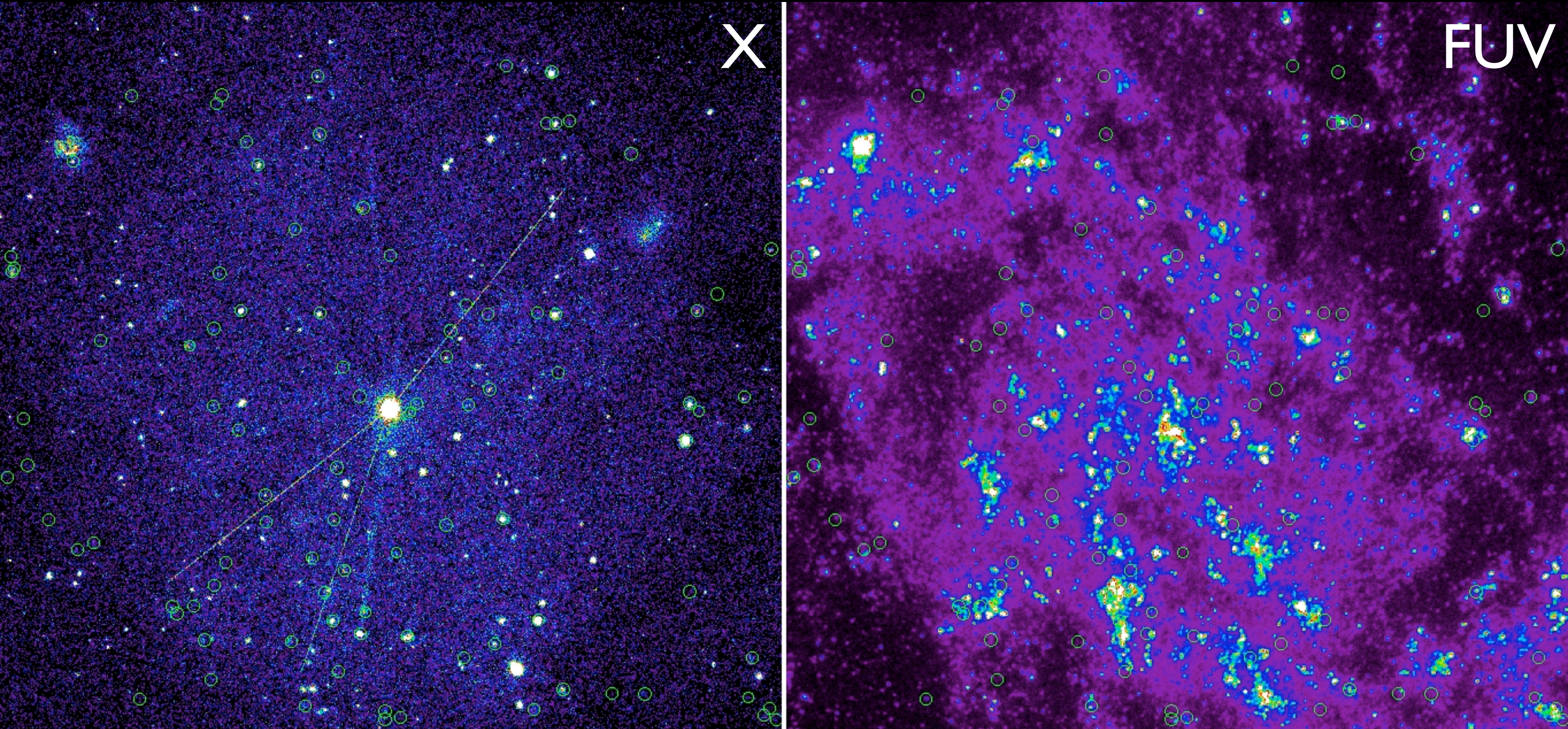
The bulk of the emission is due to star-formation.

But what does that mean?

Emission is due to SNe (mainly) + stellar winds (few percent)

Most SNe lose their identity within the bubble quickly

Only ~3% of emission from M33 in identifiable SNR



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These regions have very complicated emission

- overionized, underionized, and charge exchange
- the global galaxy spectrum is the ∑ many of these regions

➙ spectral fitting does not directly produce physical params.

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These regions have very complicated emission

- overionized, underionized, and charge exchange
- the global galaxy spectrum is the ∑ many of these regions

➙ spectral fitting does not directly produce physical params.

However...

We still fit spectra and derive "T" which then get used, e.g.

Typical galactic kT=0.25 & 0.7 keV

Typical cooling times are ~10^8 yr

In that time gas should move ~π around the galaxy...

...yet we see sharply defined spiral arms!

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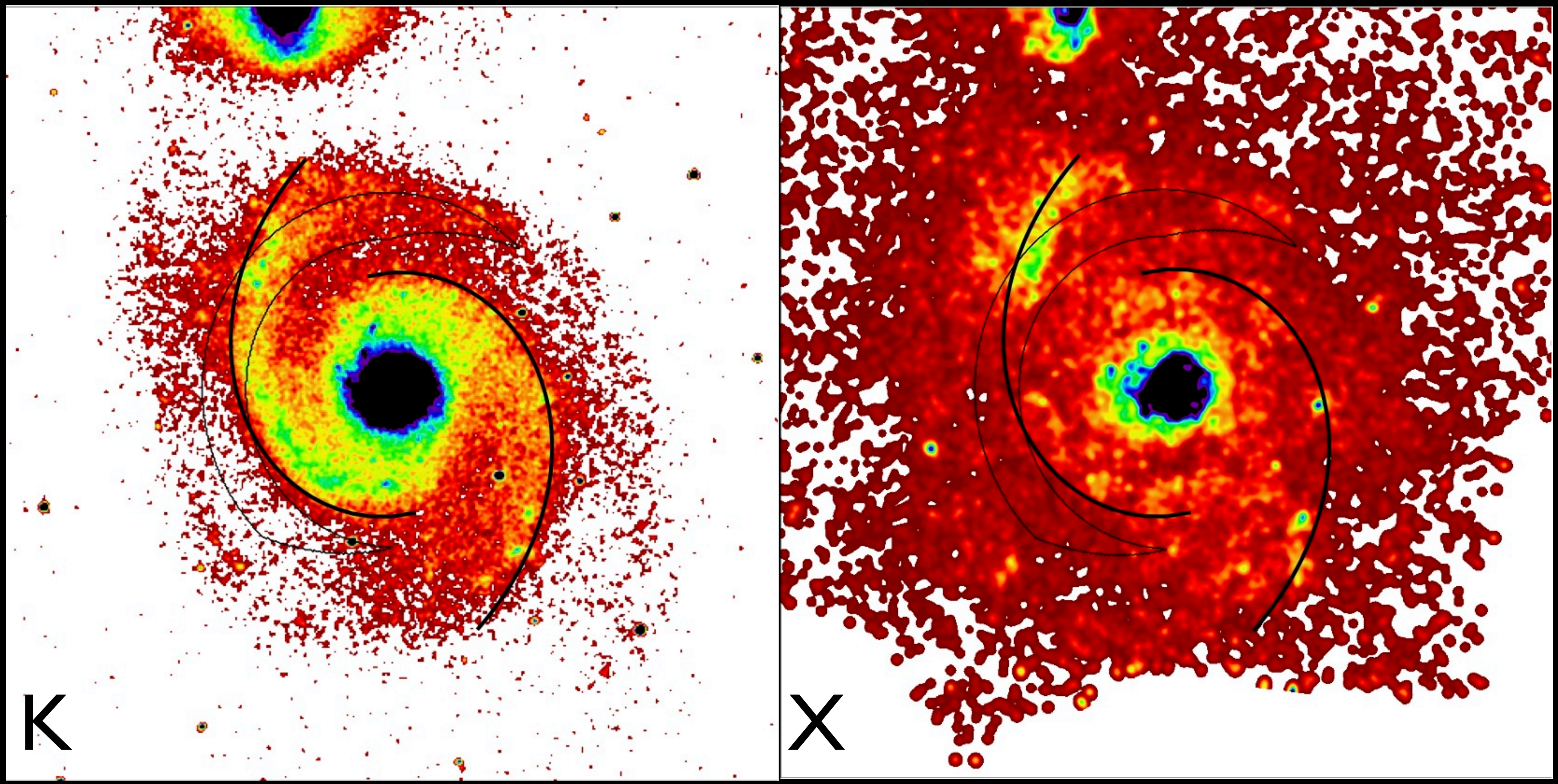
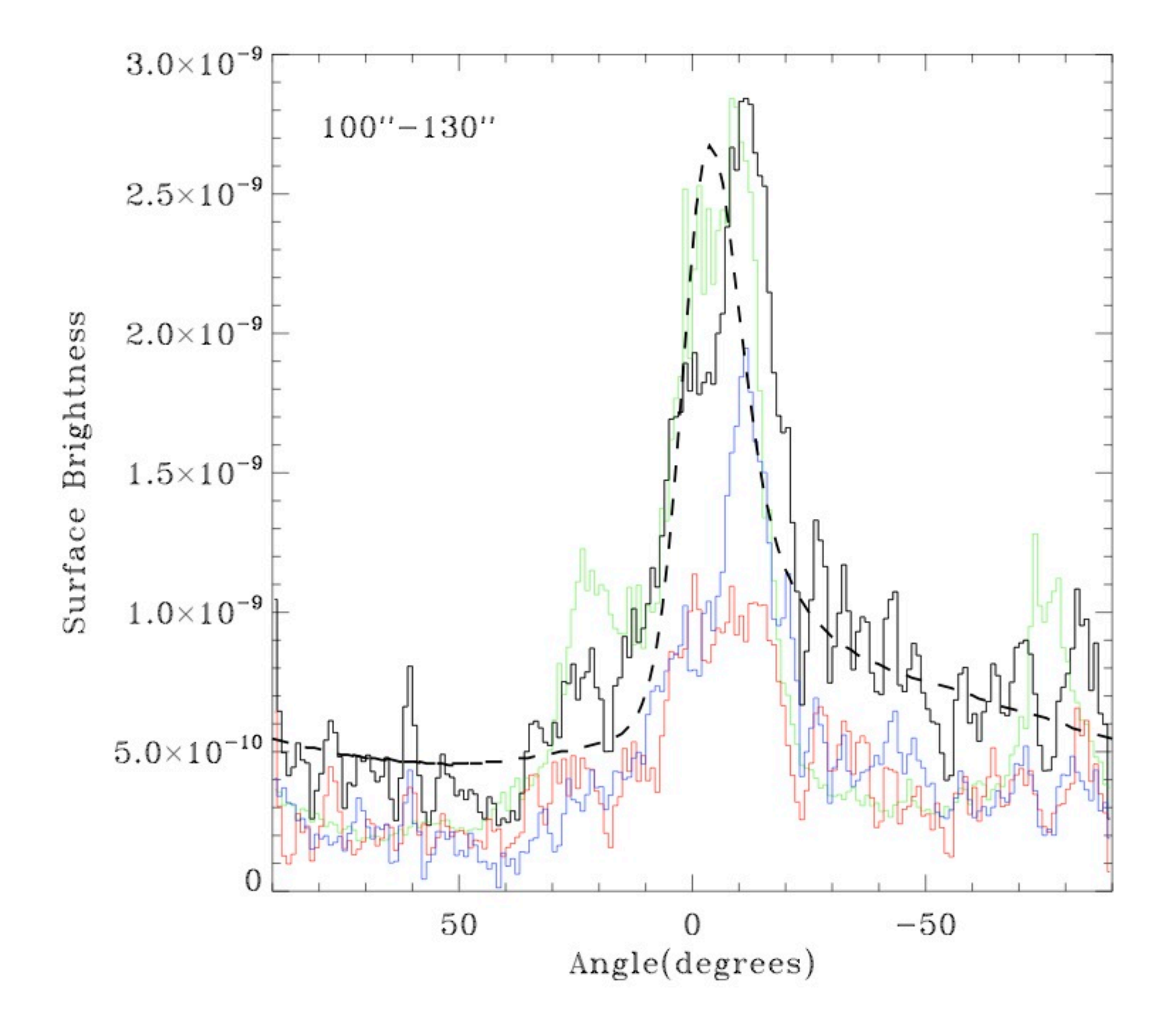


What's in a Late-Type Spiral Galaxy?

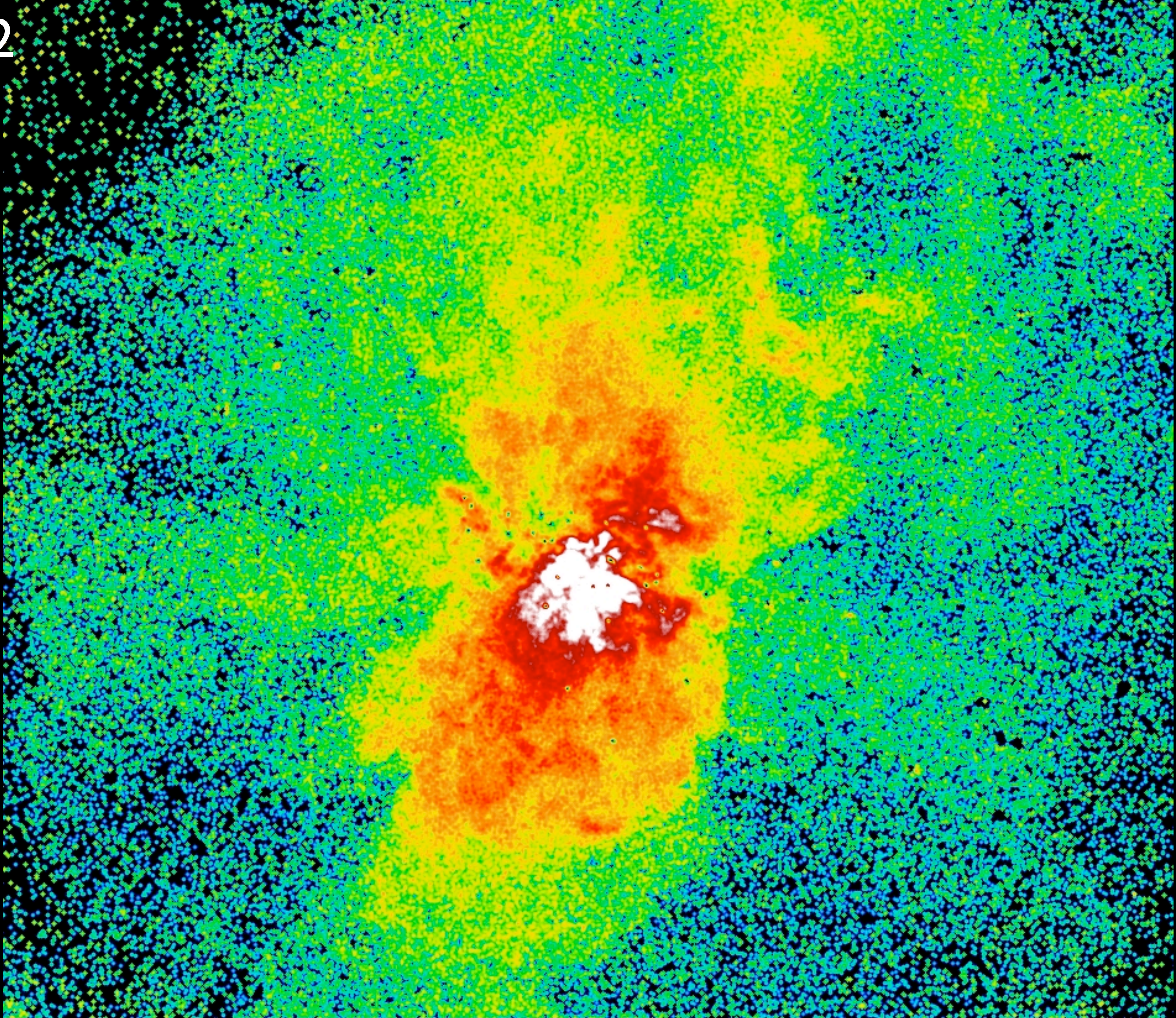
Typical galactic kT=0.25 & 0.7 keV
Typical cooling times are $\sim 10^8$ yr
In that time gas should move $\sim\pi$ around the galaxy...
...yet we see sharply defined spiral arms!

Outside arm,
Ambient P drops
Hot gas expands
Density drops
Since emission $\propto n^2$
➙ surface brightness drops



There may be more hot gas there than we can detect!

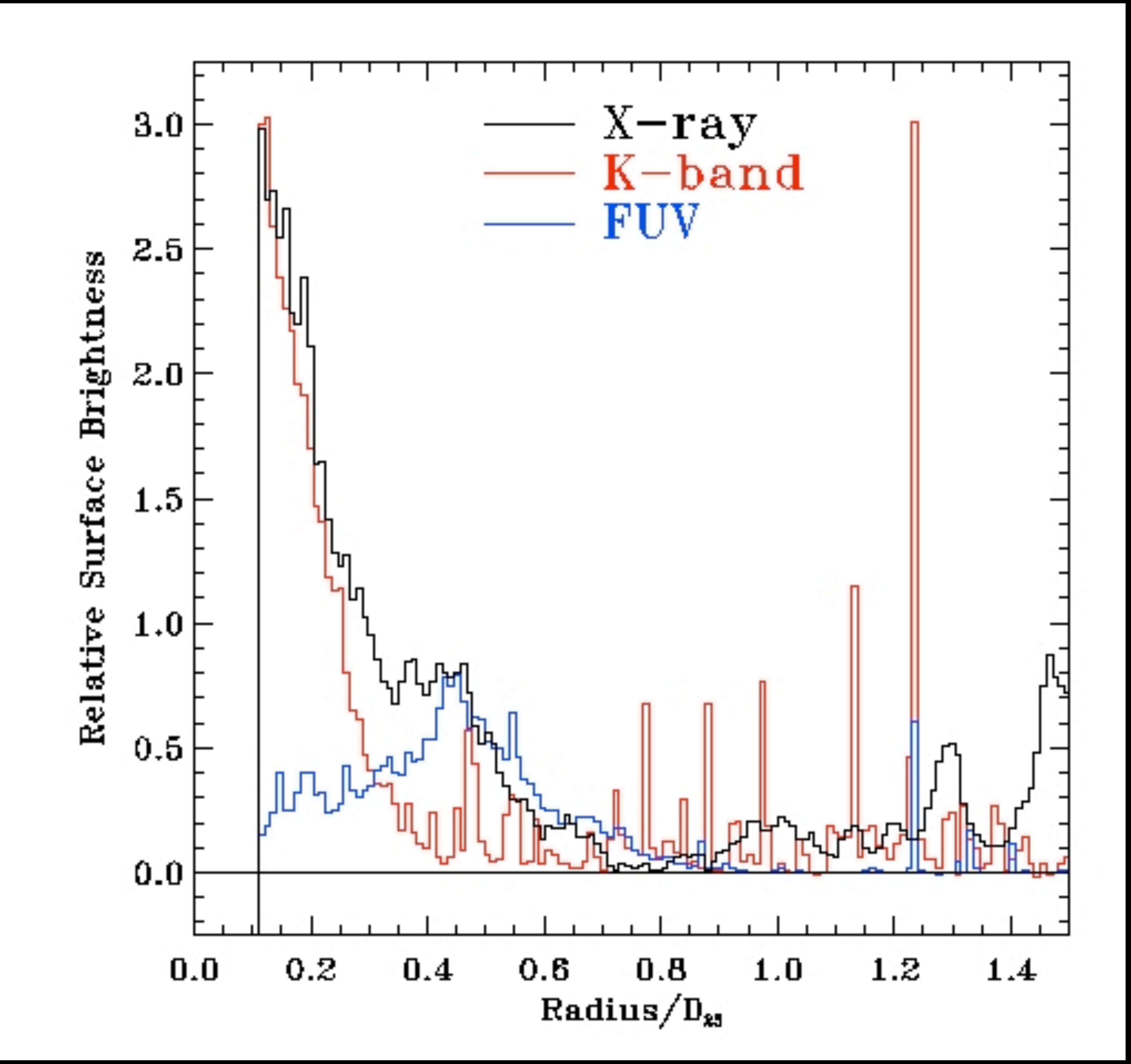
M82

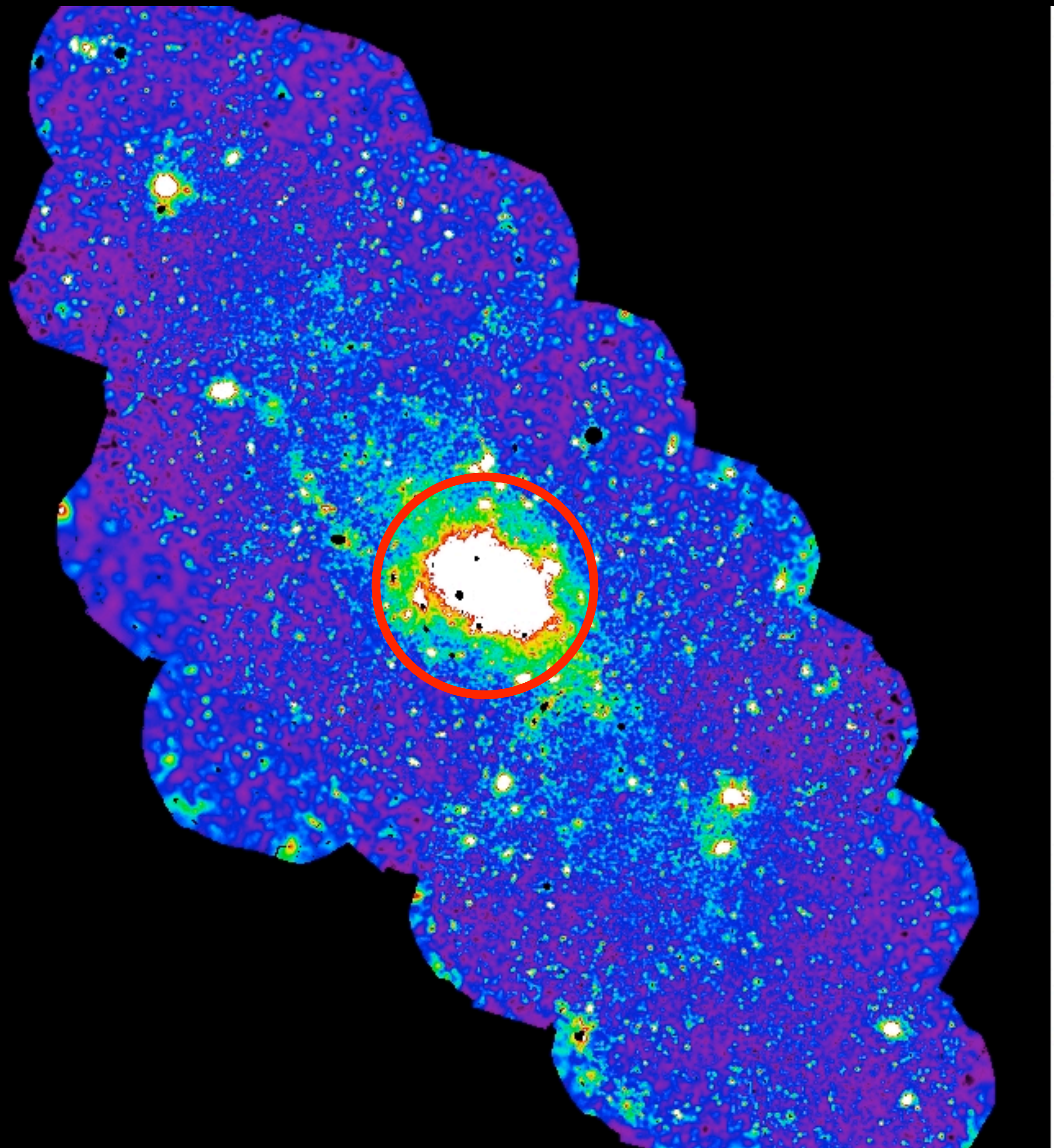


What's in an Early-Type Spiral Galaxy?

Bulge dominated

Radial profile of disk shows X-ray correlated with both FUV (star-formation) and K (stellar coronae)

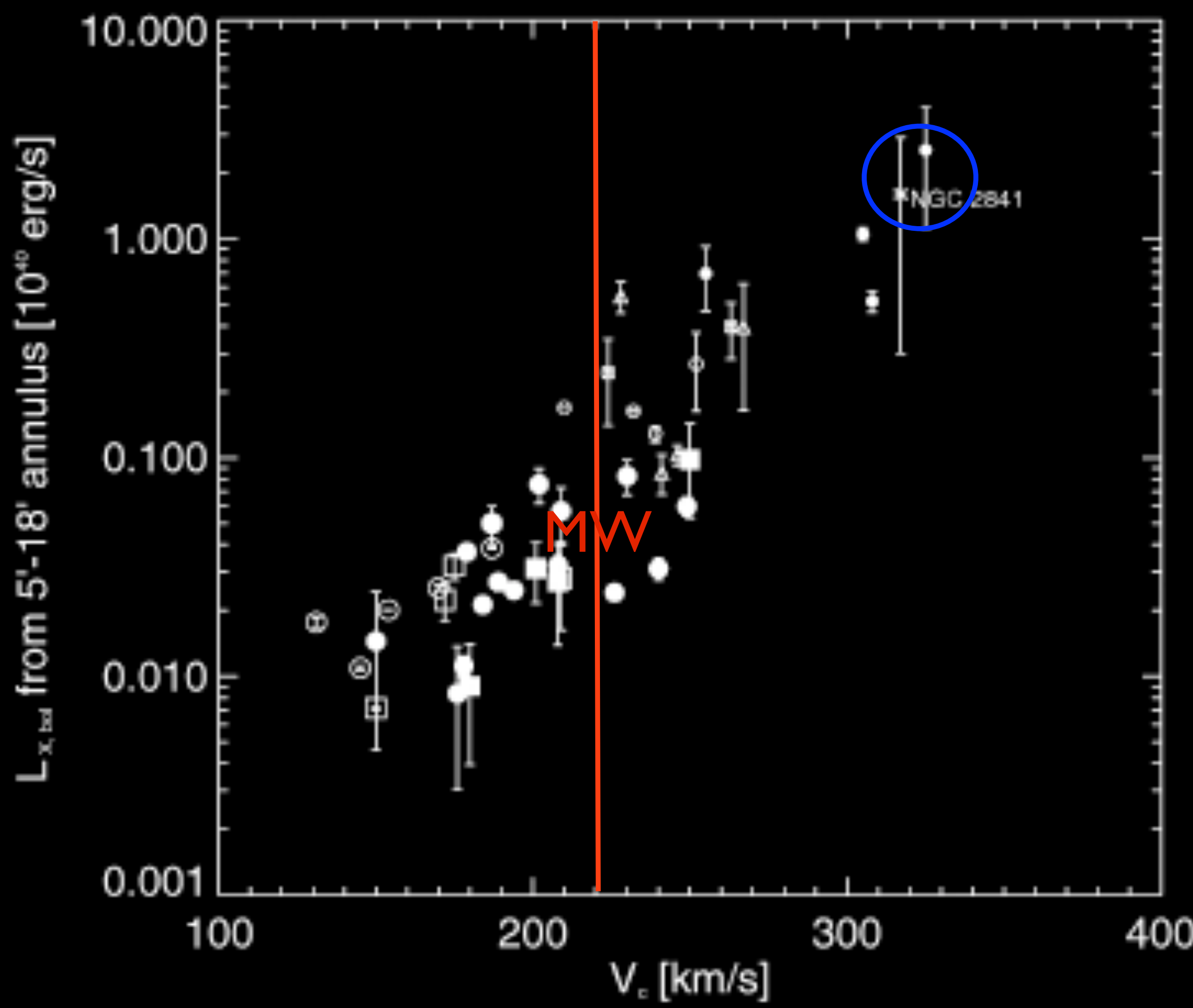




Where Are All the Haloes?

Virial temperature of MW-like galaxy is ~10^6 K

Model predictions for luminosities:



Summary

The bulk of the X-ray emission that we see in galaxies:

- is only the densest of the hot gas
  - missing all of the low density gas (much of the mass?)
- dominated by star-formation in late-type spirals (SNe that have lost their identity)
- dominated(?) by stellar coronae in early-type spirals (but very hard to verify)
- is not in spherical hydrostatic halos

Very difficult to extract physical parameters:

- multiple components along line of sight
- likely out of equilibrium (both ways)
- relatively low spectral resolution (CCDs)

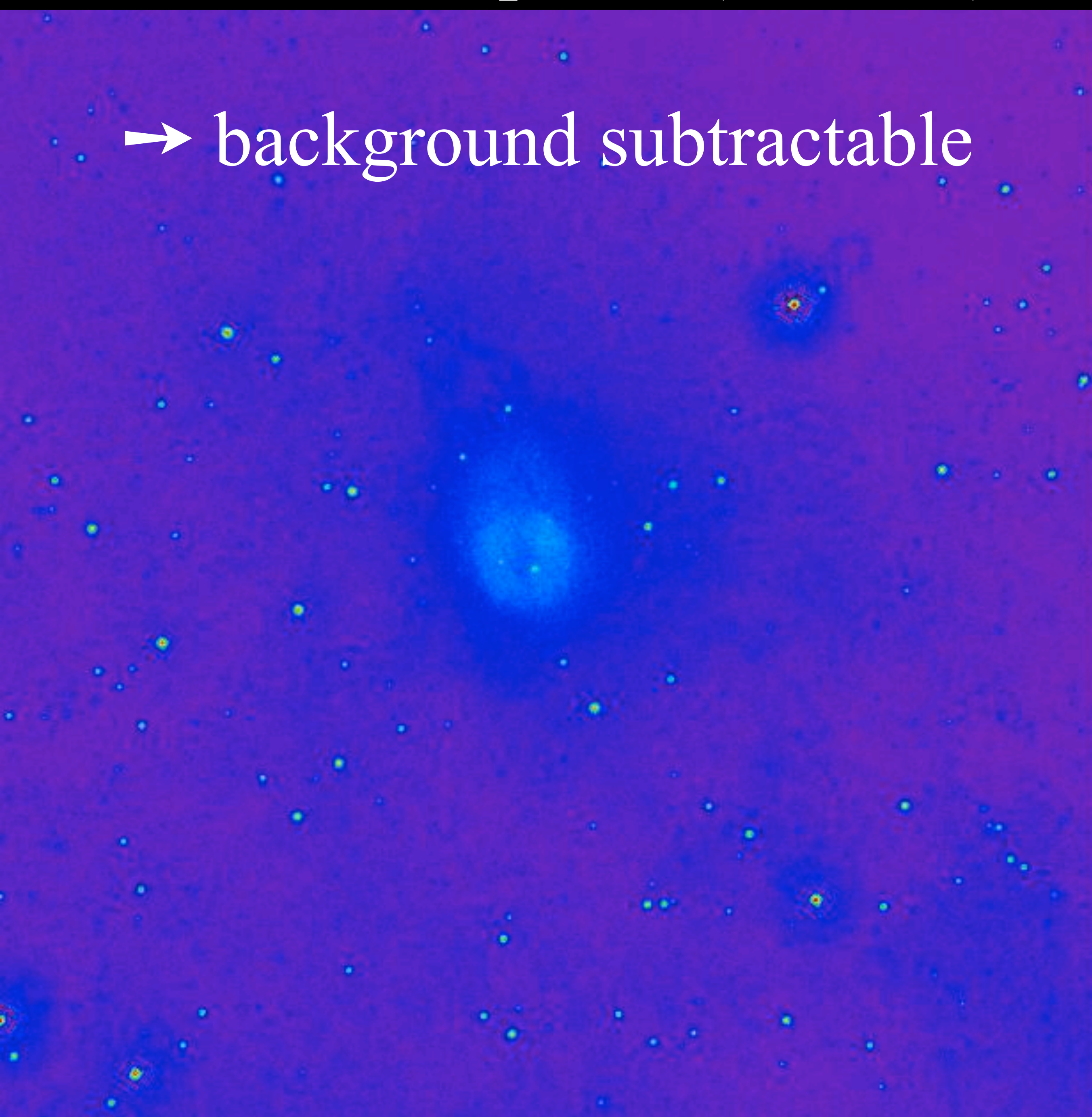
Correlations are beginning to emerge that hint at the physics

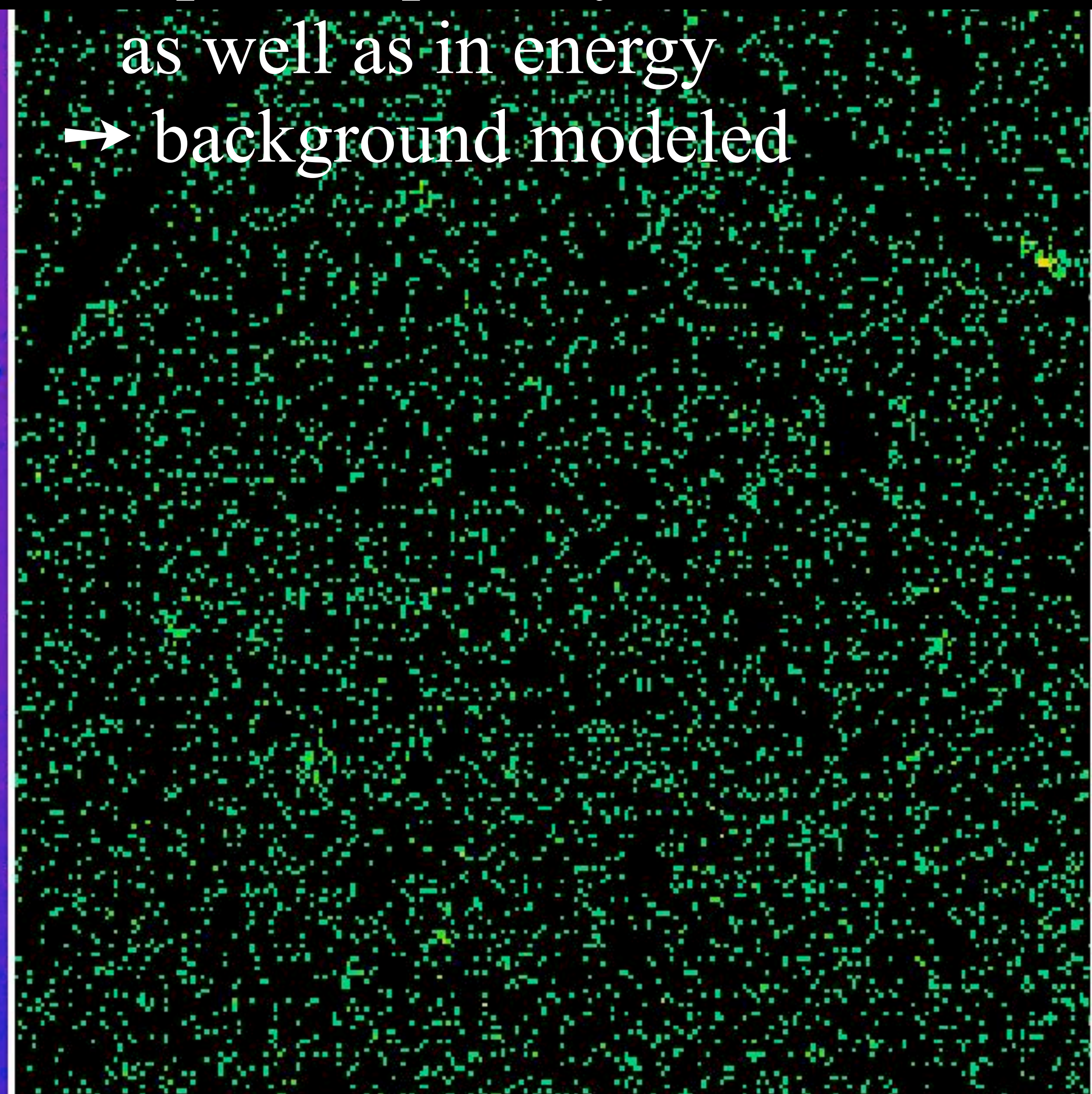
X-ray vs. Optical Analysis

Bandpass set by instrument
Many counts/pixel
→ small background region
Uniform response (flatfield)

→ background subtractable

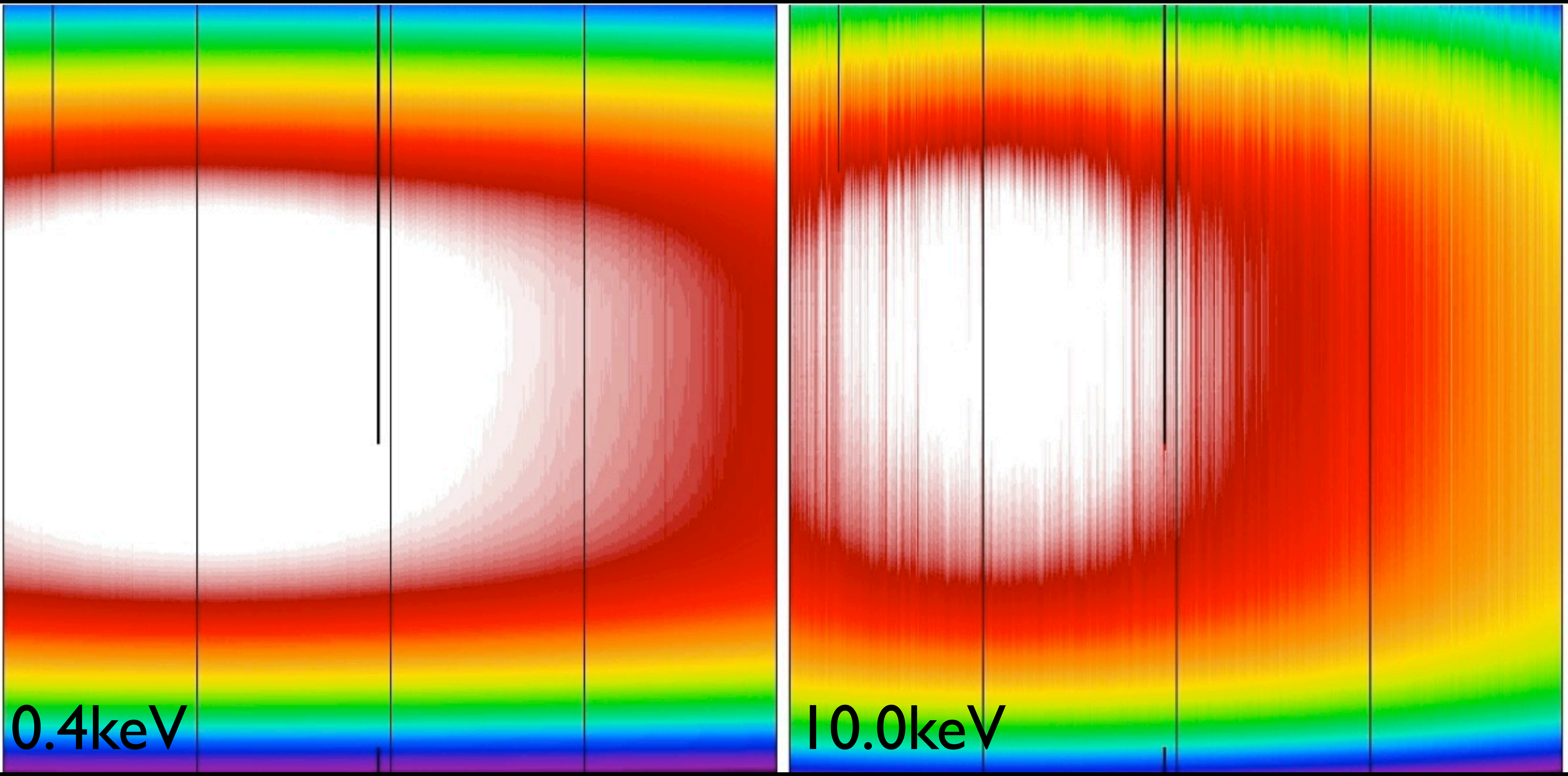
Bandpass set by user
Less than one count/pixel
→ large background region
Response spatially variable
as well as in energy
→ background modeled





How Much Does RMF Variation Matter?

Relative Responses for ACIS-S3



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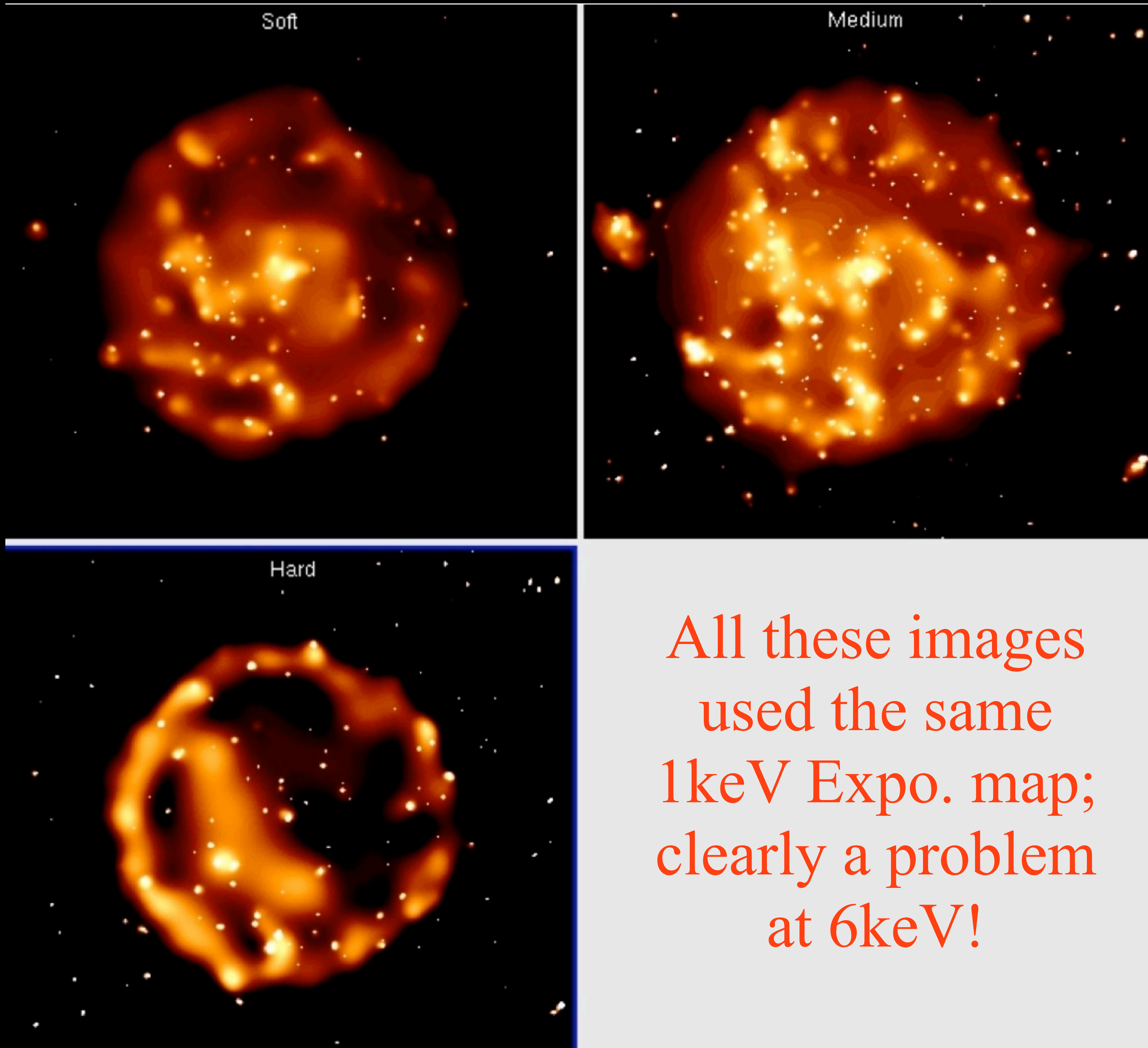
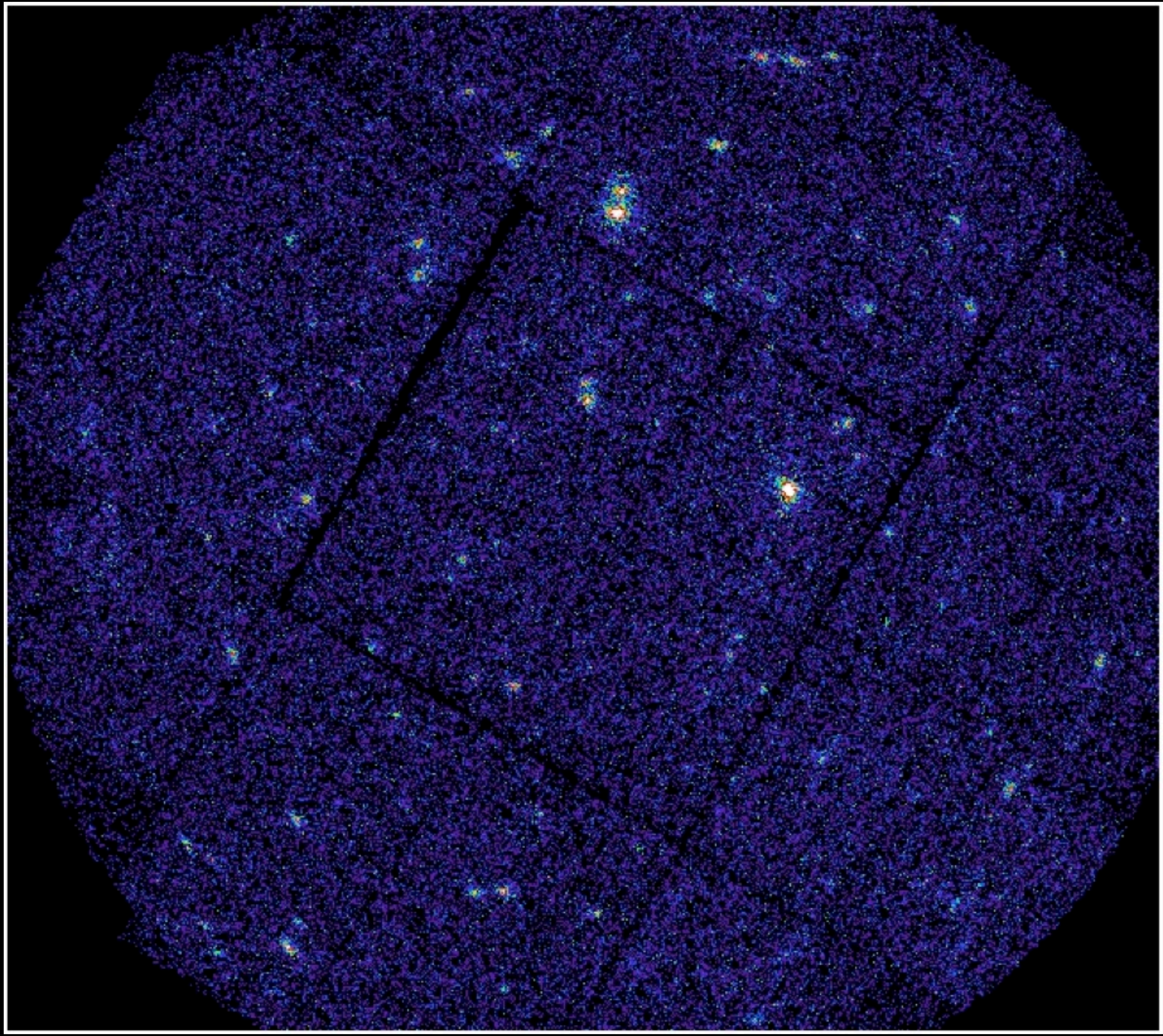


All these images used the same 1keV Expo. map; clearly a problem at 6keV!

Background Removal Strategy

Which photons in this image are due to the background?



Backgrounds (What they are)

Non-Cosmic Backgrounds:	
Energetic Particles	Spatial dist. & energy resp.
"Soft" Protons	≠ photon dist. & resp.
Local Backgrounds:	
Scattered Solar X-rays	Non-uniform distribution
Solar Wind Charge Exchange	Uniform distribution
Cosmic Backgrounds:	
Local Hot Bubble	
Galactic Halo	
Unresolved AGN	

Background Removal Strategy

Spectroscopy:

Best Practice:

FIT all components simultaneously,

FIT background and source simultaneously

2nd Best Practice:

Subtract the backgrounds you must &

FIT the rest

Imaging:

Best Practice:

1) build count (not count rate) images for each background
2) subtract all the backgrounds from the image
3) divide the remainder by the response

Imaging can't be done without spectroscopic analysis

Spectroscopy can't be done without imaging analysis

Backgrounds

Non-Cosmic Backgrounds:

Energetic Particles

- pass through instrument from all directions
- interact directly with the detector
  ➙ events can look like X-rays
- interact with material around detector
  ➙ X-ray emission
- spatially variable (not like photons)
- may be temporally variable
  XMM is, Chandra not

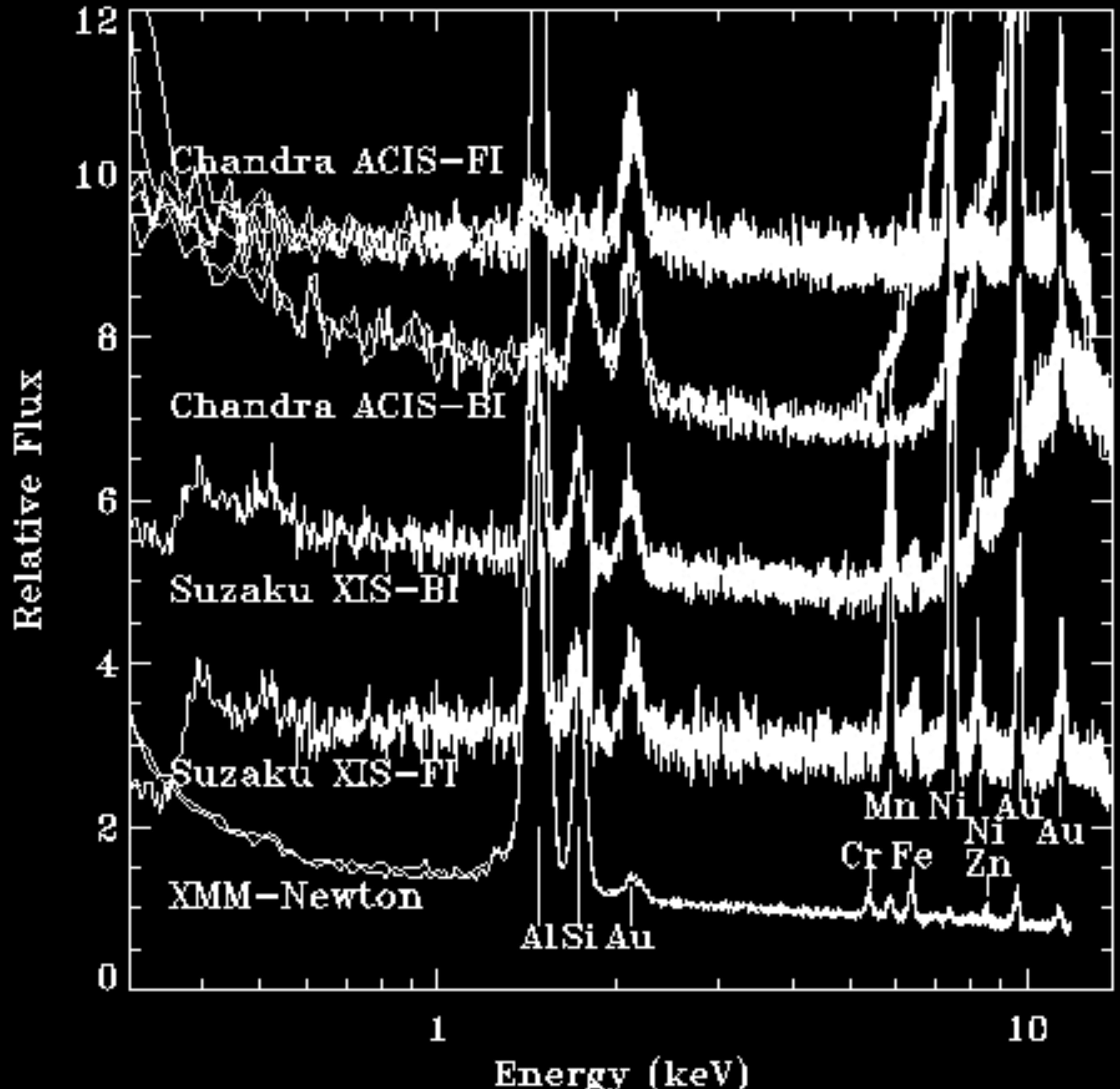
Coping:

- Missions produce particle background files
  images and spectra (depending on mission)
  - created by closing filter wheel or observing dark earth
  - normalize to observation at high E, $\gtrsim$10 keV

Backgrounds

Non-Cosmic Backgrounds:

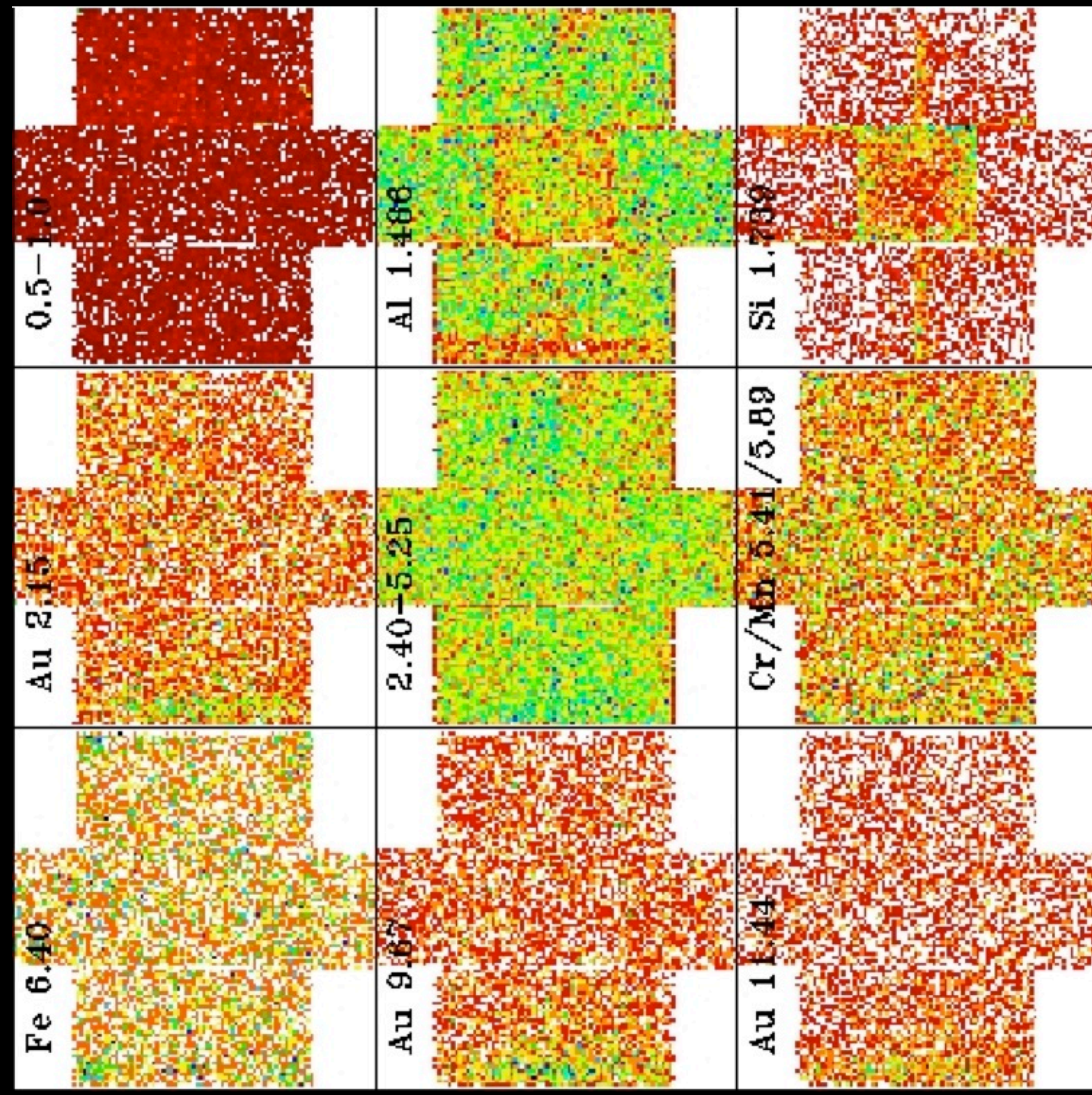
Energetic Particles



Backgrounds

Non-Cosmic Backgrounds:

- Energetic Particles
  - Spatial Distribution:
    - XMM: features
    - Chandra: flatter



Backgrounds

Non-Cosmic Backgrounds:

"Soft" Protons ("Soft Flares")

- MeV protons focussed by optics onto detectors (oops!)
- Strongly time variable (in strength and spectrum)
- Spectrum often broken or cutoff power law

Coping:

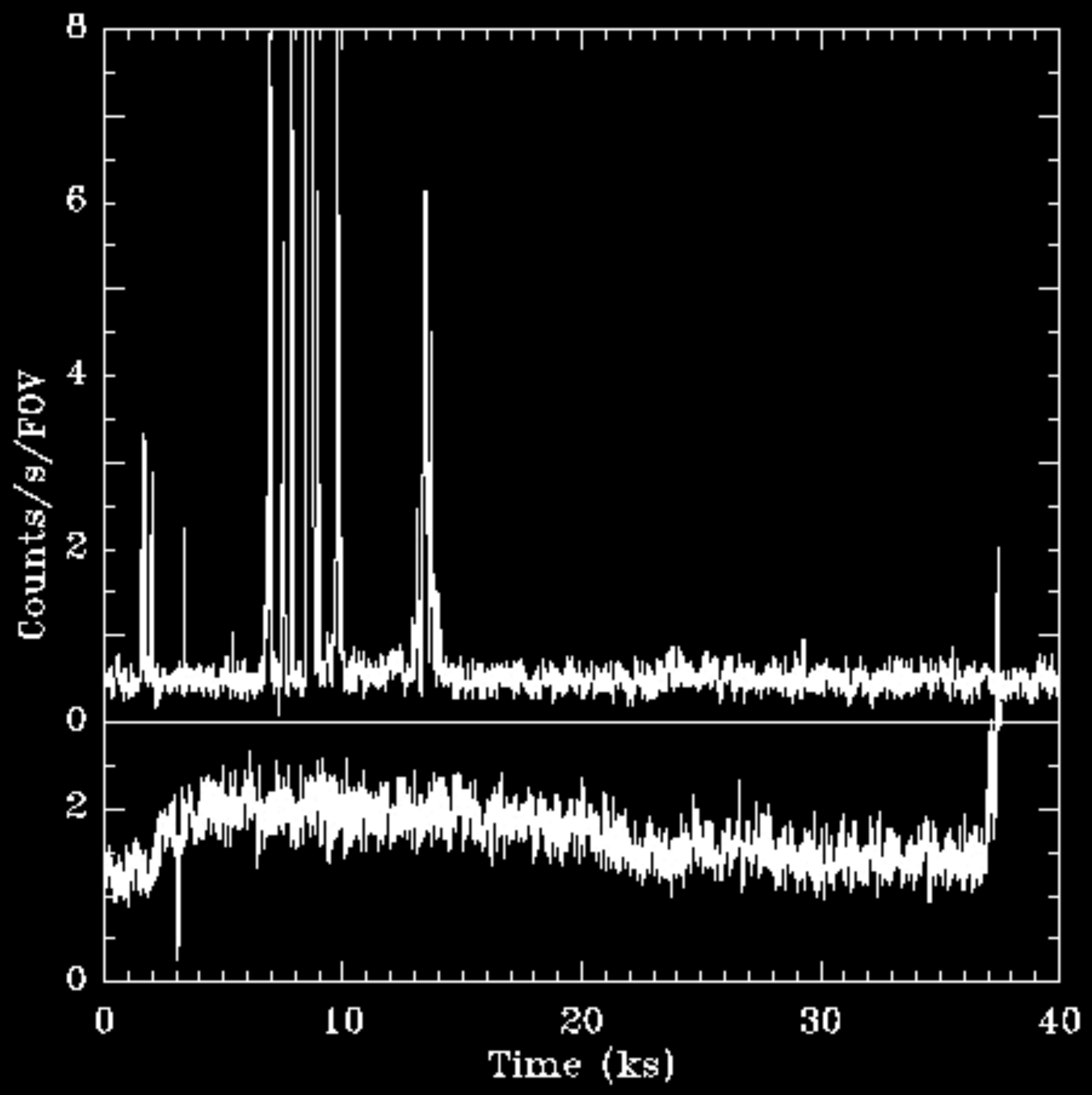
- Filter out times with flares (will reduce noise)
- Fit the remainder
- Apply spectroscopic normalization to "flare map" and subtract from image

Backgrounds

Non-Cosmic Backgrounds:

"Soft" Protons ("Soft Flares")

Two XMM light-curves - sometimes flares are not obvious

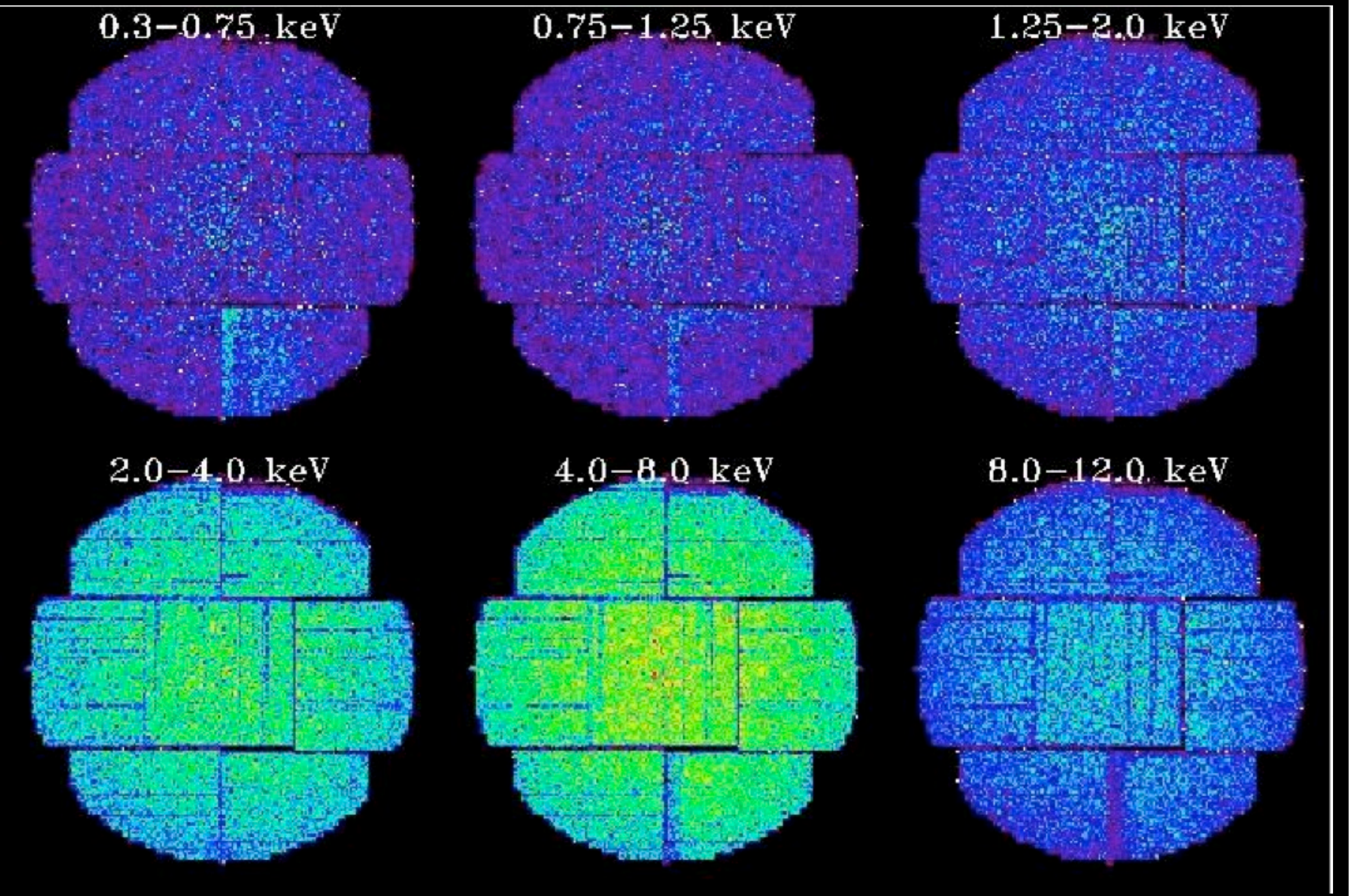


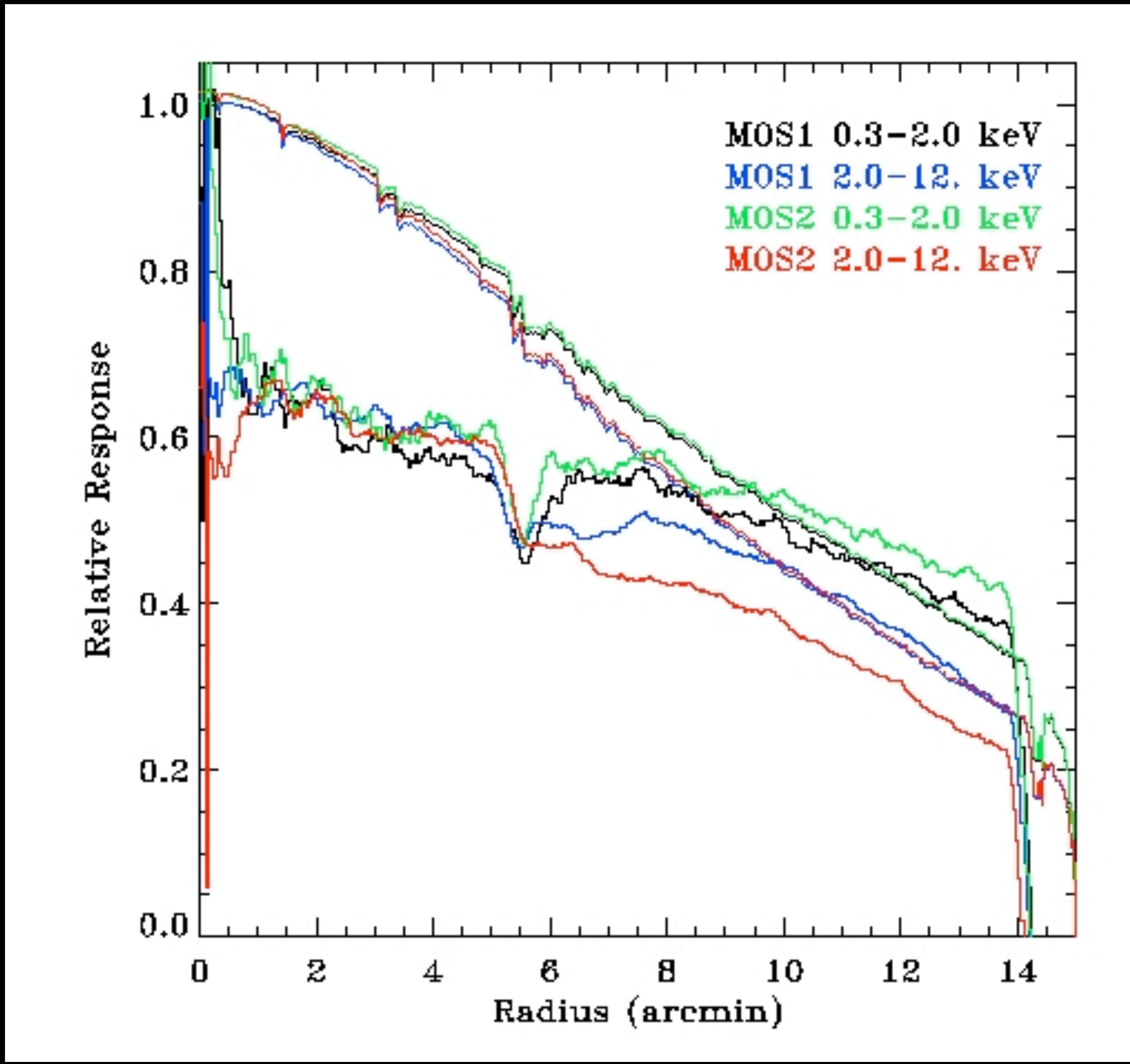
Backgrounds

Non-Cosmic Backgrounds:

"Soft" Protons ("Soft Flares")

Spatial distribution is flatter than that of photons





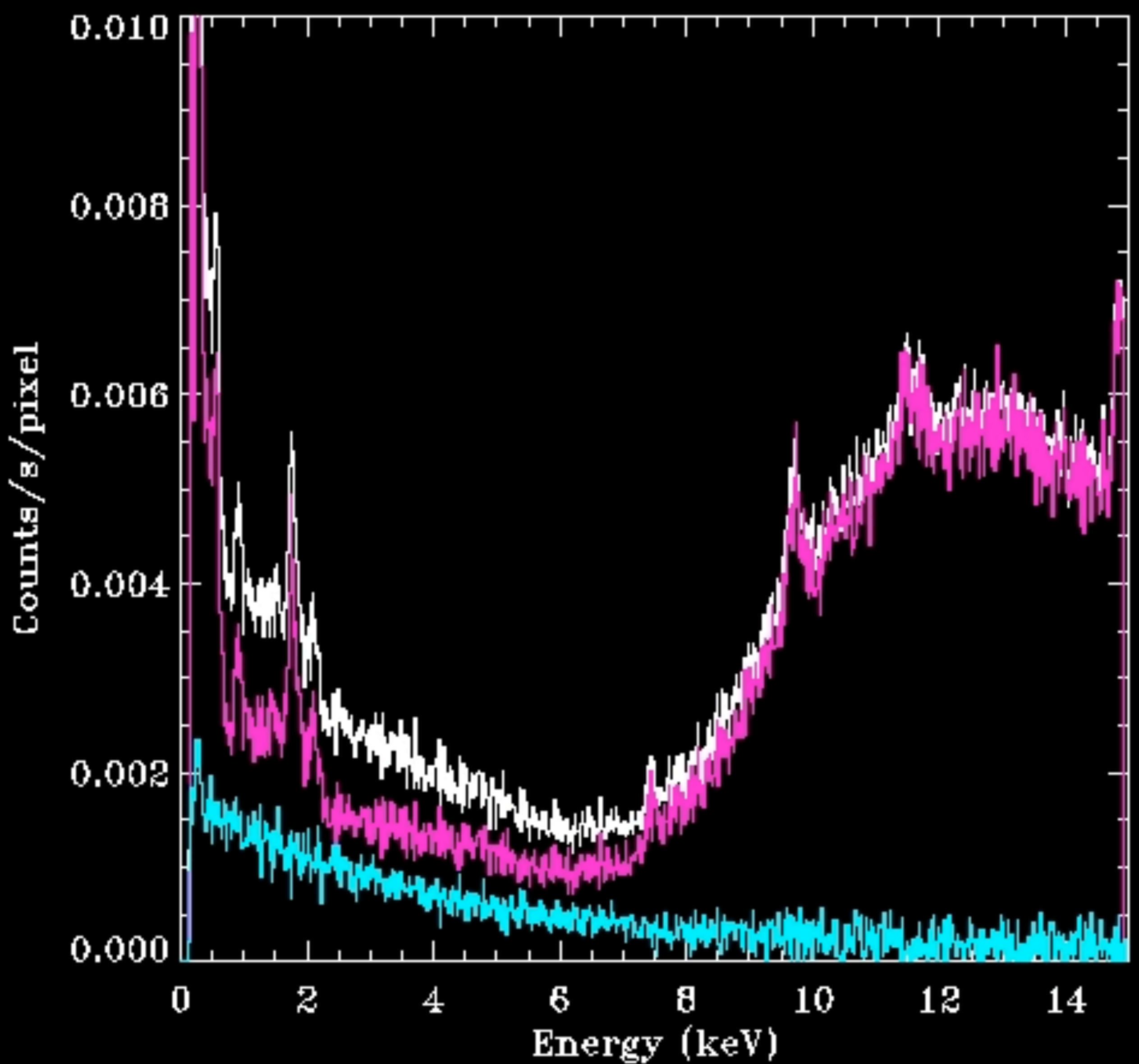
Backgrounds

Non-Cosmic Backgrounds:

“Soft” Protons (“Soft Flares”)

Mean spectrum ~ broken power law - but large variation

A “flared” XMM spectrum, a “cleaned” spectrum, and their difference (showing spectrum of a set of flares)



Backgrounds

Local Backgrounds:

Scattered Solar X-rays (from Earth's atmosphere)

- Only a problem for missions looking close to the earth (ROSAT, Suzaku)

Coping:

- Remove contaminated data

Solar Wind Charge Exchange (SWCX)

- Temporally variable, particularly at O VII and O VIII
- Compare O-band light curves with higher energy

Coping:

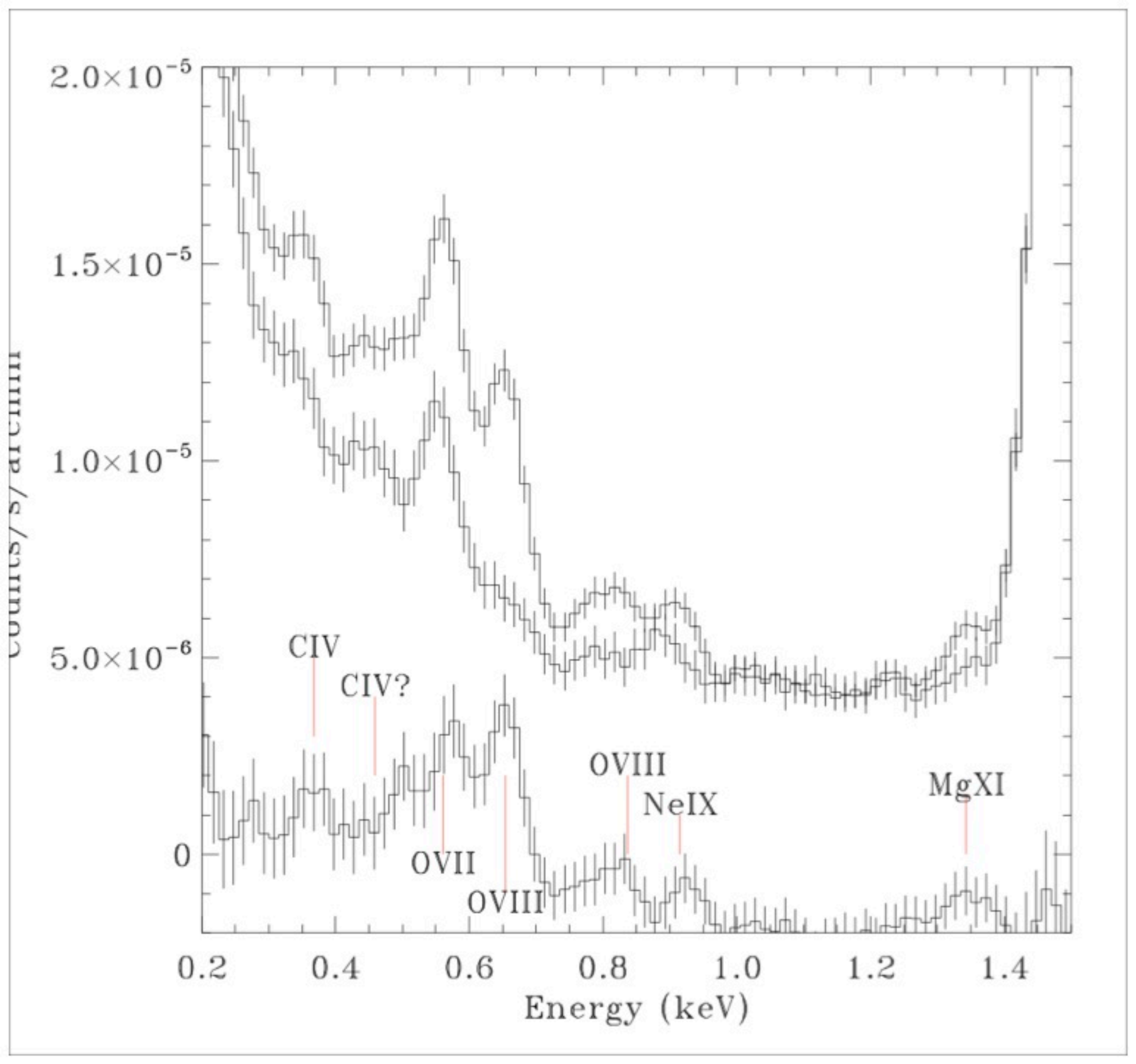
- Give the data to someone who studies SWCX (Unless the species hit by SWCX aren't of interest)

Backgrounds

Local Backgrounds:

Solar Wind Charge Exchange (SWCX)

Two XMM observations of exactly the same direction:



Backgrounds

Cosmic Backgrounds:

Local Hot Bubble:

- unabsorbed thermal component with kT~0.09 keV

Galactic Halo

- thermal component with kT~0.25 keV +
- (sometimes) thermal component with kT~0.09 keV
- absorbed by total Galactic N(H) along line of sight

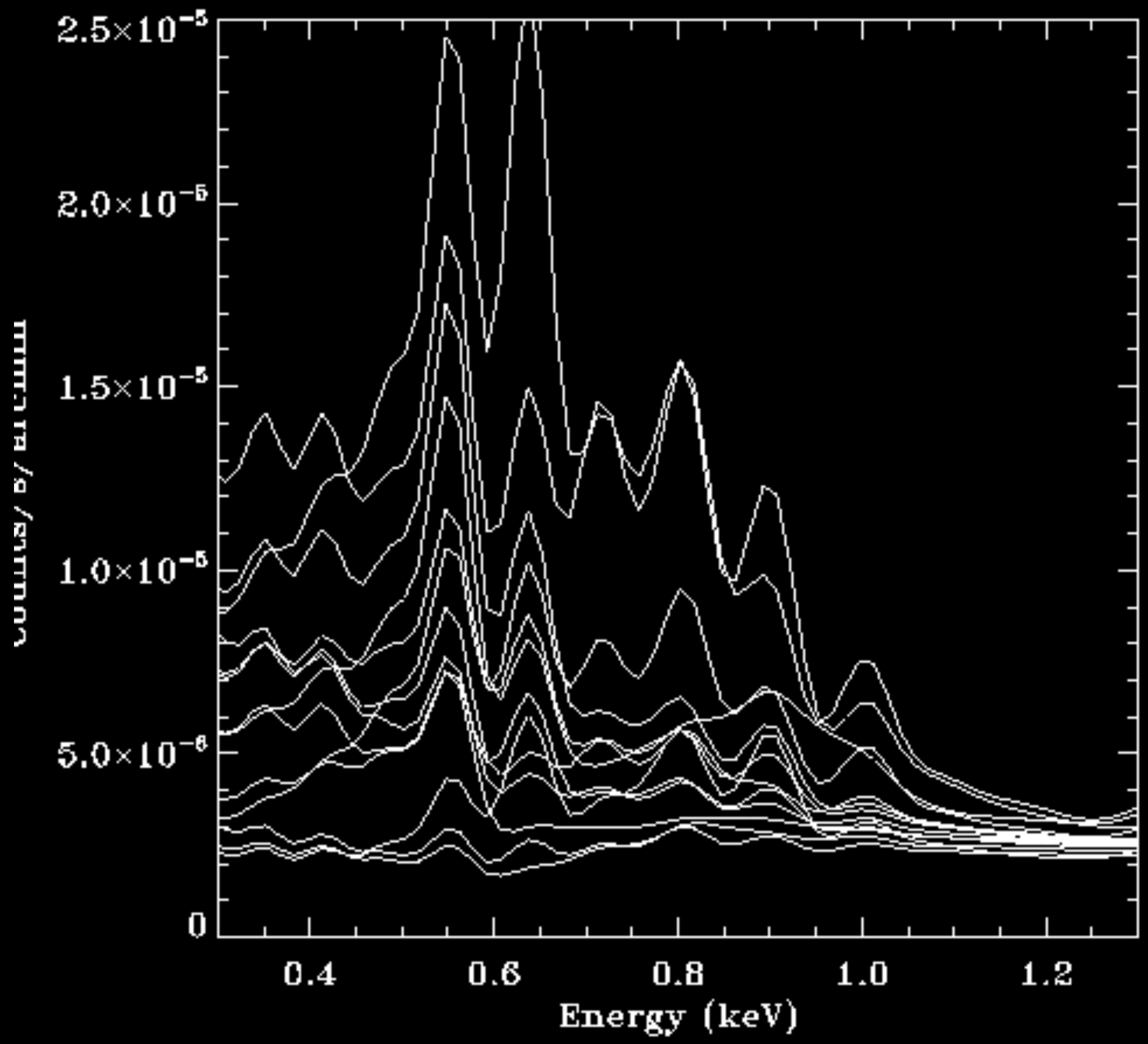
Coping:

- Fit simultaneously!
- Do not use “background” or “empty field” spectra or images below ~1.5 keV!

Do Not Use Mean Backgrounds

Cosmic Backgrounds:

- The cosmic background varies greatly with direction.
- A “mean” cosmic background is rarely correct.



Backgrounds

Cosmic Backgrounds:

Unresolved AGN

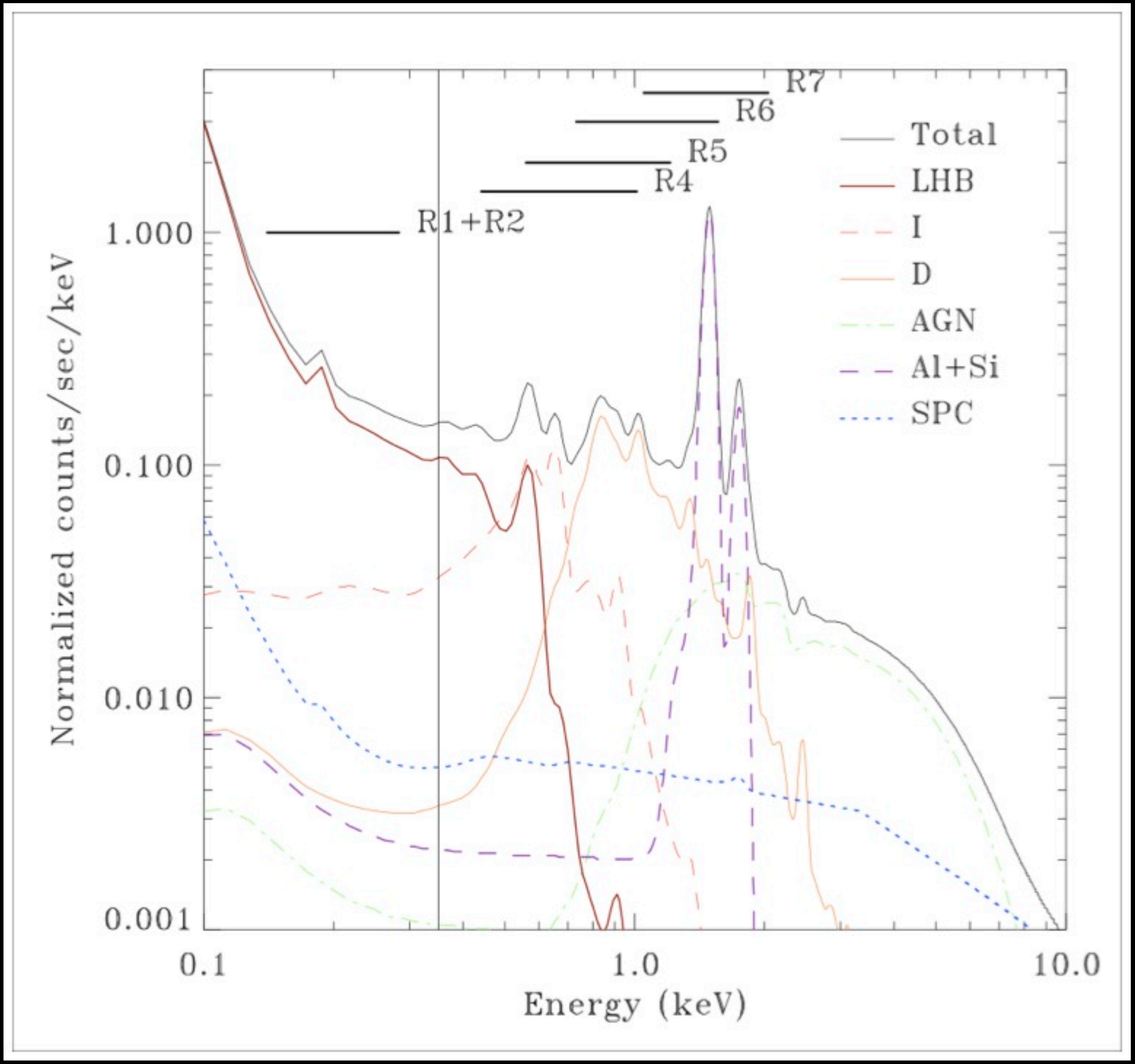
- power law spectrum with Γ=1.46 absorbed by Gal.N(H)
- normalization depends on point-source detection limit (but easily calculated using, e.g., Cappelluti et al 2009)

Coping:

Fit simultaneously, allow norm. to vary (within reason)

Background Example

An example of all of the components in an XMM spectrum of "empty sky"



Backgrounds (Example)

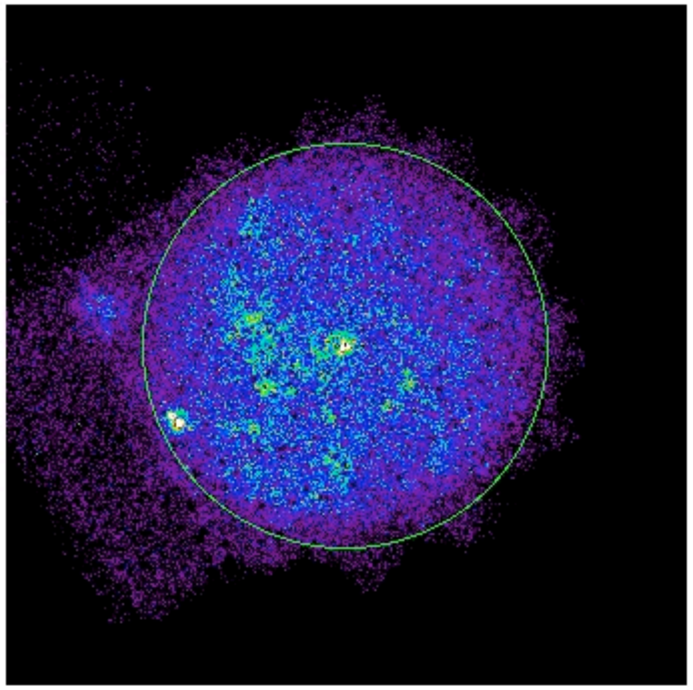
The Analysis of M101 -

Where to get the background for a Chandra analysis?

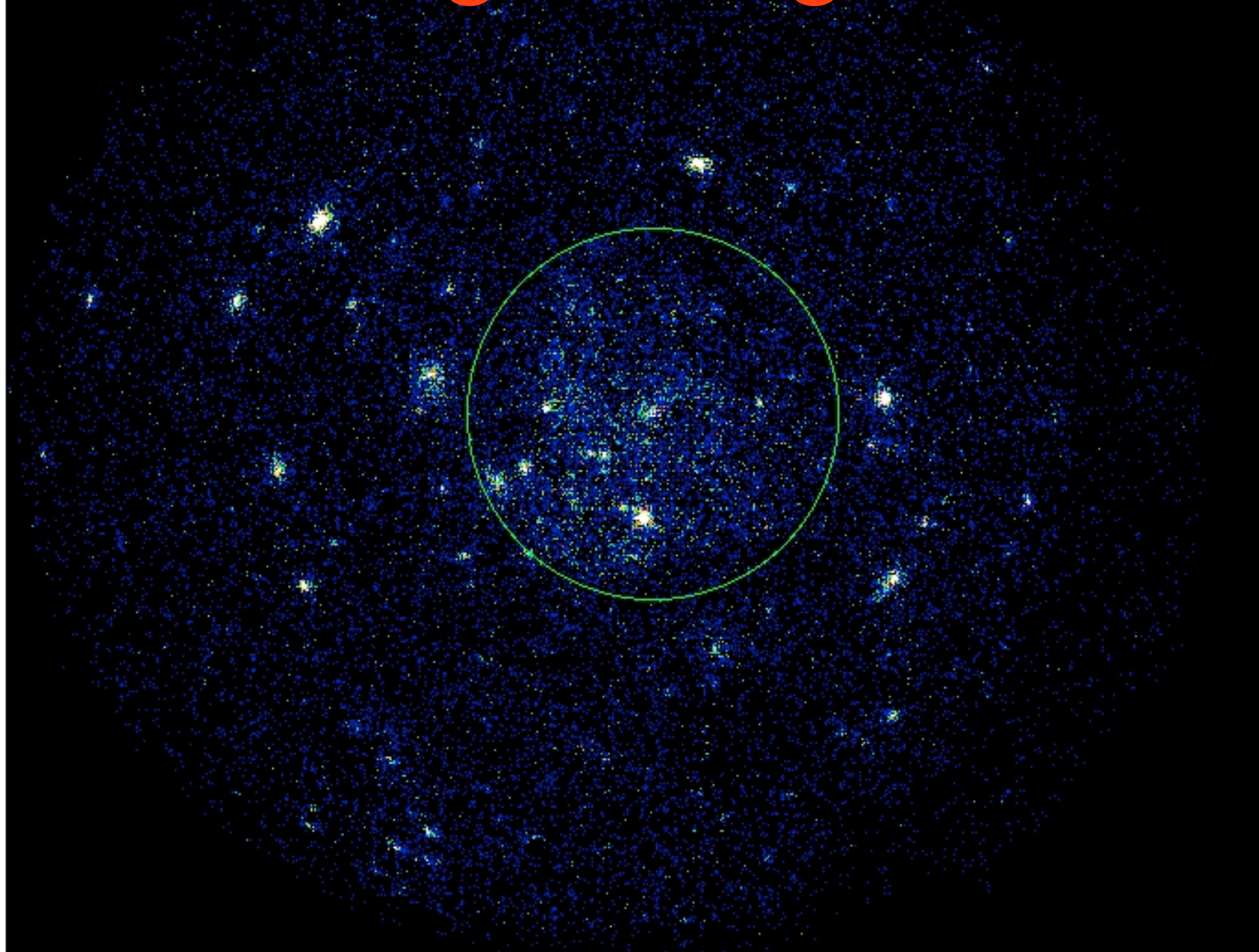
Since response in background region ≠ in source region

- not restricted to same detector or even same telescope

Chandra image for which we need background



XMM image from which we can get background

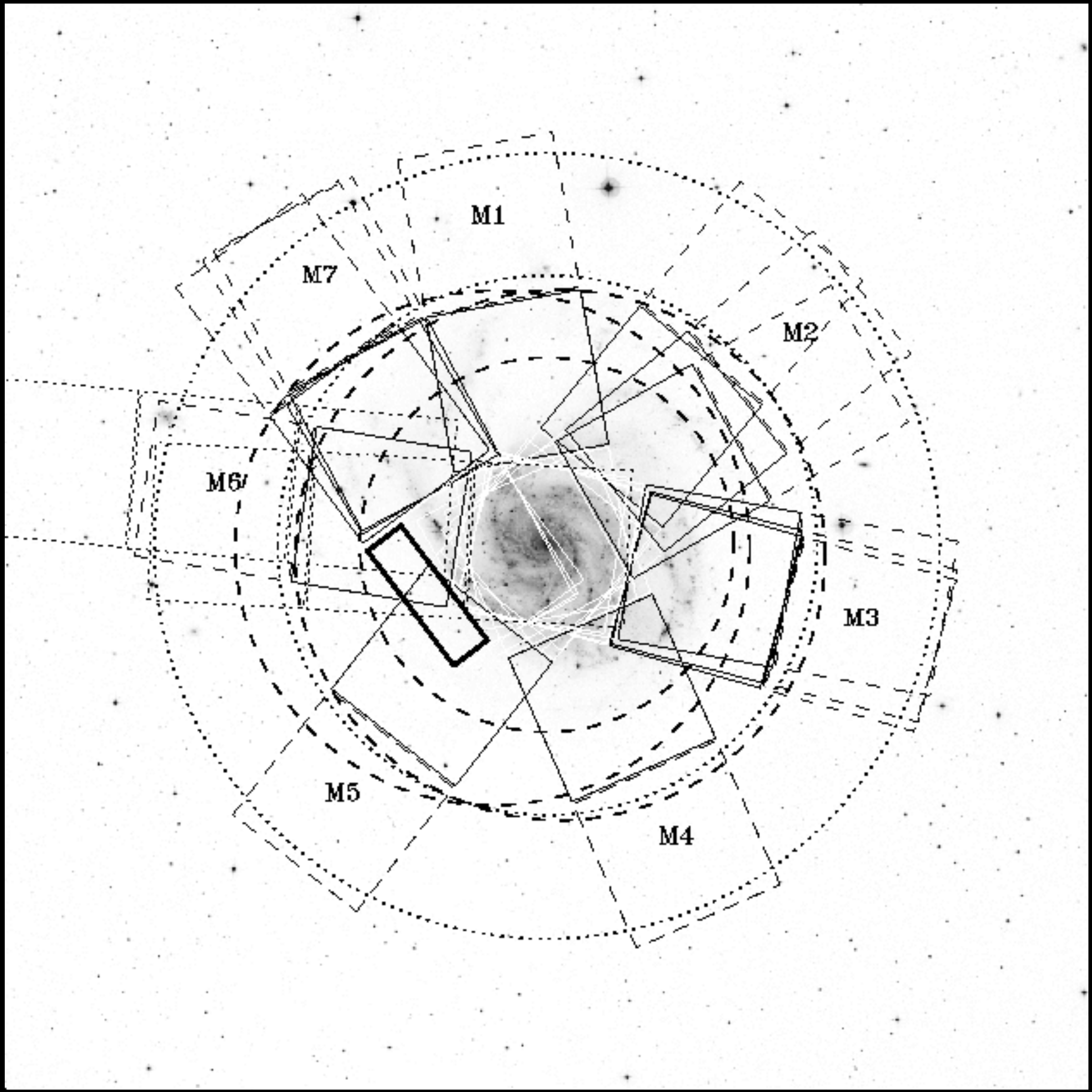


Backgrounds (Example)

The Analysis of M101 -

Where to get the background for a Chandra analysis?

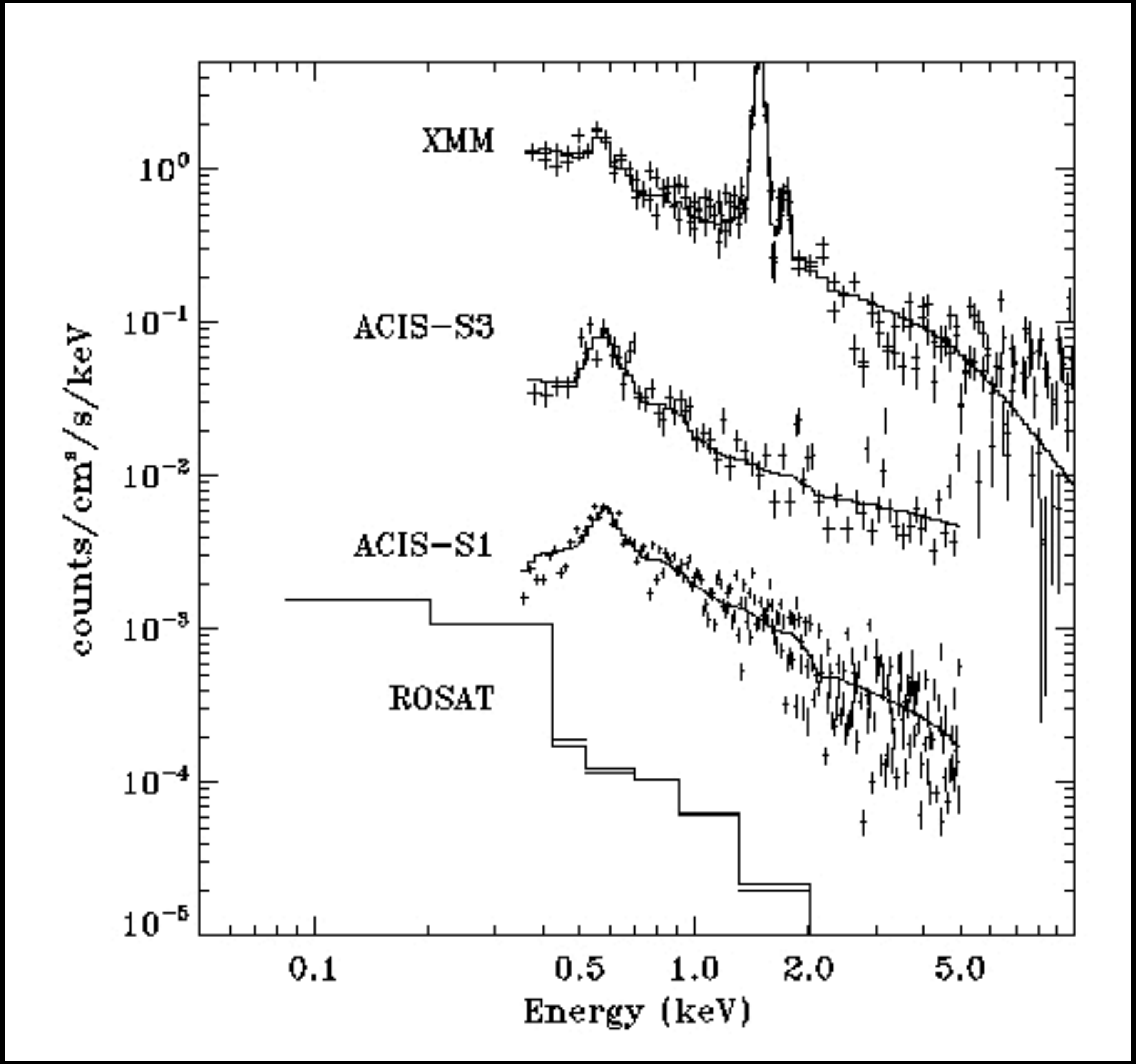
S1 chip can also be used to get background for S3



Backgrounds (Example)

The Analysis of M101 -

Fitting the backgrounds - different instruments consistent

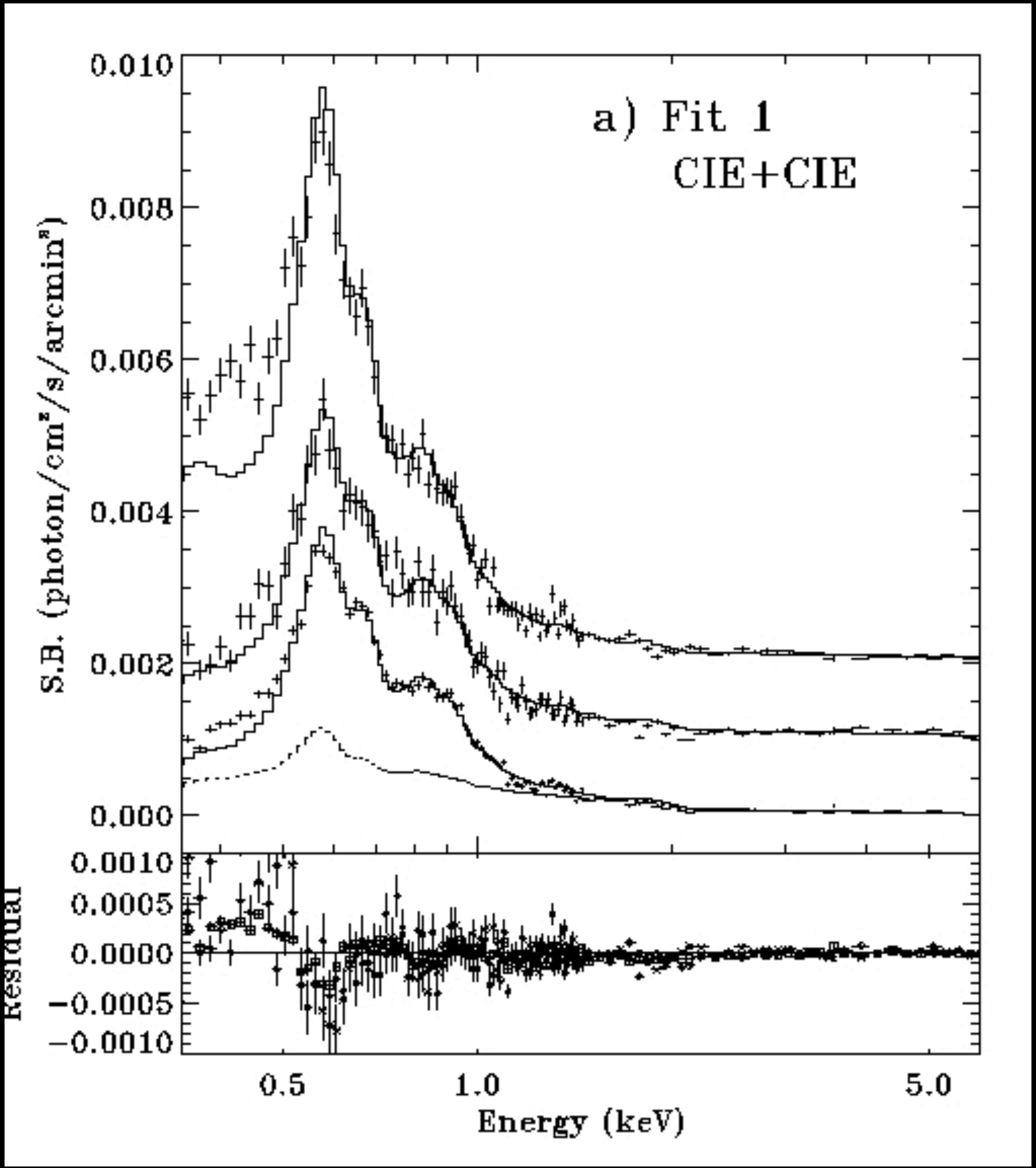


Use these fit parameters to create background images.

Backgrounds (Example)

The Analysis of M101 -

Then use scaled background in fit of the source spectra



Backgrounds ()

Non-Cosmic Backgrounds:

- Energetic Particles
- “Soft” Protons

Local Backgrounds:

- Scattered Solar X-rays
- Solar Wind Charge Exchange

Cosmic Backgrounds:

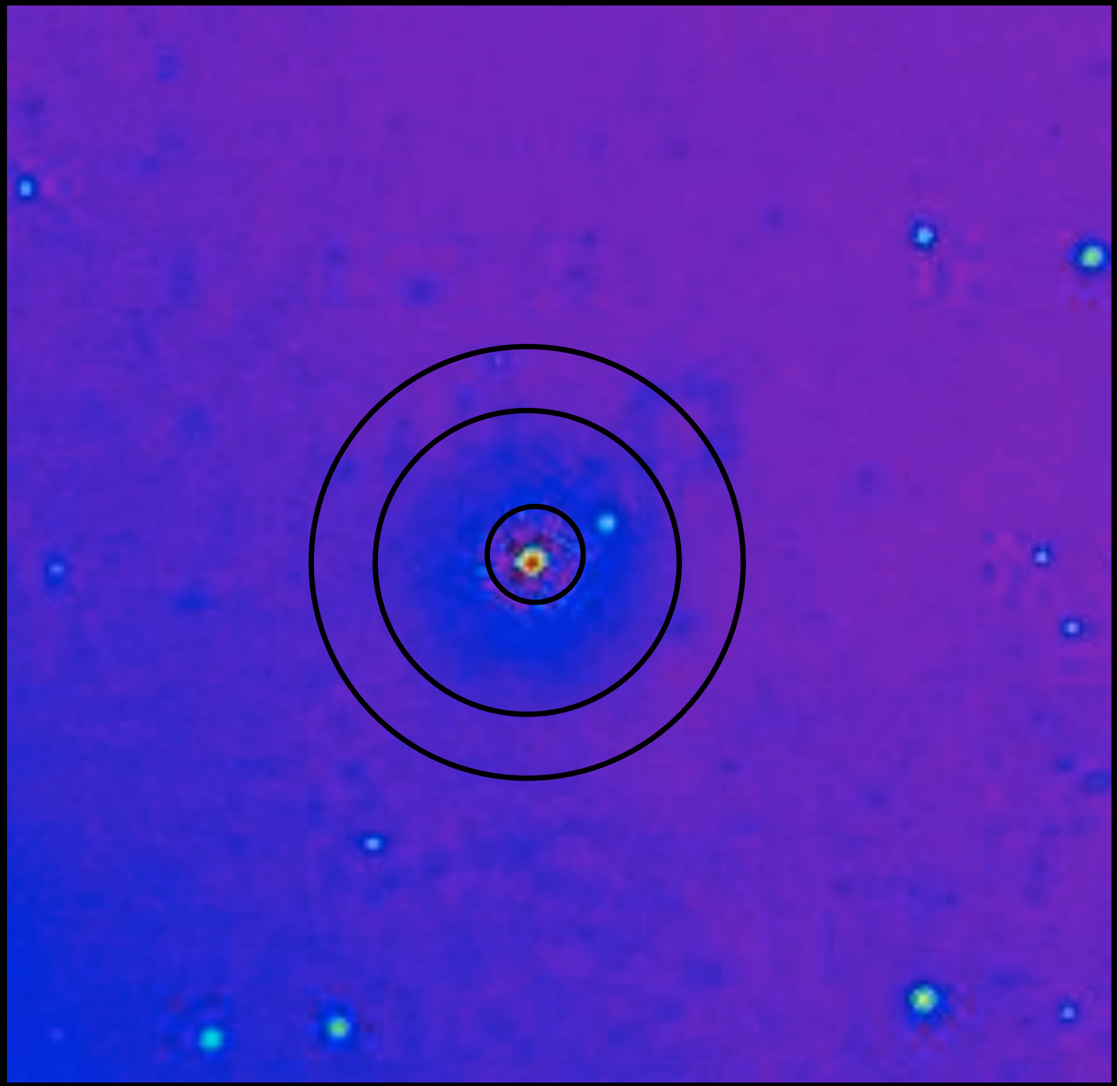
- Local Hot Bubble
- Galactic Halo
- Unresolved AGN

Analysis of Diffuse Emission

Classical optical photometry:

- Narrow band-pass is set by the instrument
- User sets object & background apertures
- Background statistically well determined

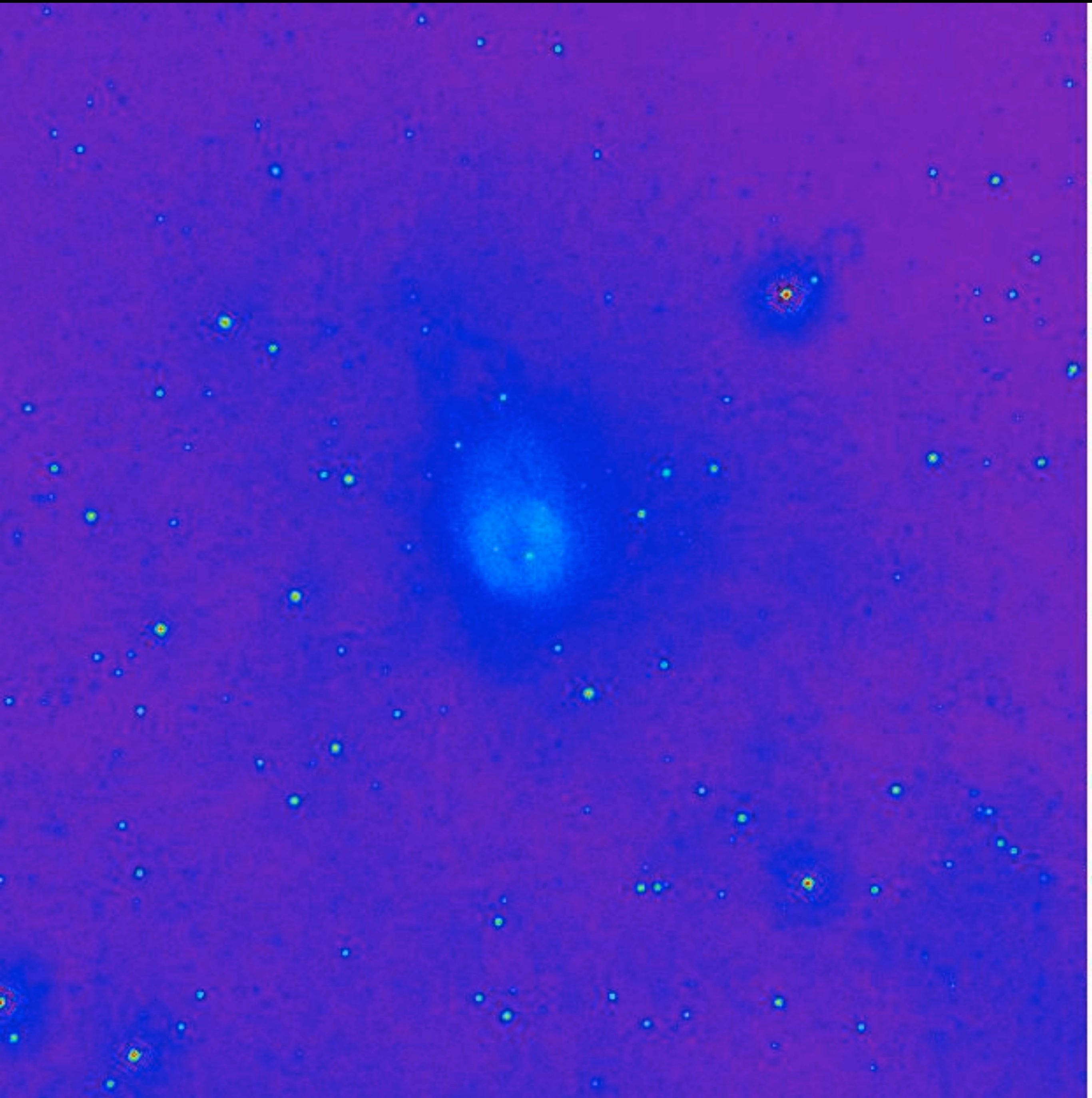
$F=(C_O-C_B*A_O/A_B)*R$

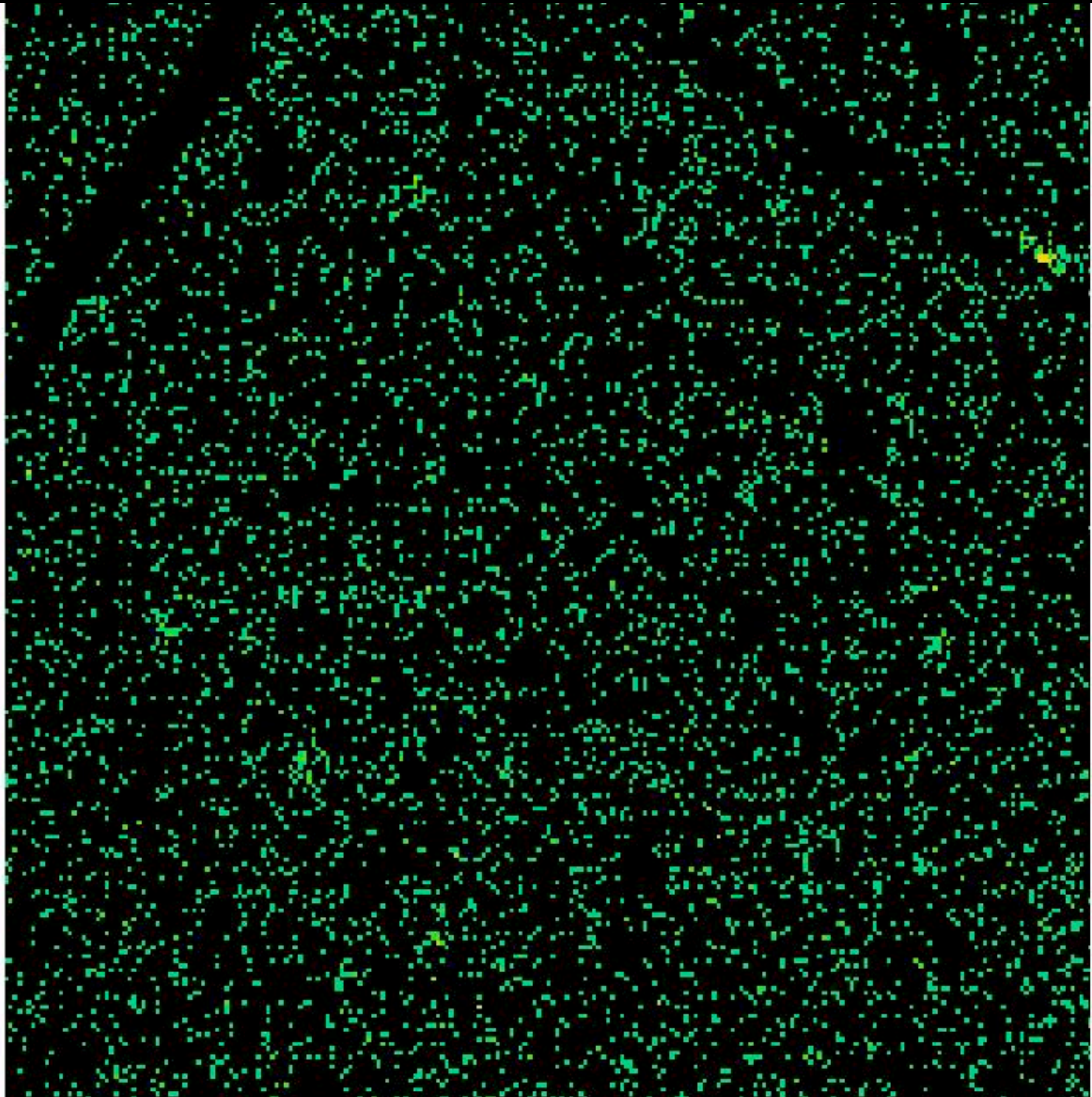


Analysis of Diffuse Emission

X-ray photometry of small sources:

- Broad band-pass is set (somewhat) by the user
- User sets source & background apertures
- Background NOT statistically well determined





Analysis of Diffuse Emission

X-ray photometry & spectroscopy of extended sources

- Background count-rate low ➙ need large area
- Response varies with position and energy ➙ R(Pos,E)
  - ➙ objects with same flux, same position, but different spectra produce different count rates
  - ➙ R=R(Pos,Spectrum)≡R(P,S)

$$F=(C_O-C_B(A_O/A_B)(R(P=O,S=B)/R(P=B,S=B)))/R(P=O,S=O)$$